

## **EARTH SCIENCE DIVISION**

### **TABLE OF CONTENTS**

Annual Performance Goal 1.1.8	Page	2
1.1.8.1 Atmospheric Composition		2
1.1.8.2 Carbon Cycle & Ecosystems		14
1.1.8.3 Climate Variability & Change		22
1.1.8.4 Earth Surface & Interior		32
1.1.8.5 Water & Energy Cycle		44
1.1.8.6 Weather & Atmospheric Dynamics		58
 Annual Performance Goal 1.1.9	Page	66
1.1.9.1 Atmospheric Composition		66
1.1.9.2 Carbon Cycle & Ecosystems		78
1.1.9.3 Climate Variability & Change		81
1.1.9.4 Earth Surface & Interior		91
1.1.9.5 Water & Energy Cycle		94
1.1.9.6 Weather & Atmospheric Dynamics		100
 References	Page	107

**Annual Performance Goal 1.1.8: NASA shall demonstrate progress in characterizing the behavior of the Earth system, including its various components and the naturally-occurring and human-induced forcings that act upon it.**

**Section 1.1.8.1 Atmospheric Composition Focus Area**

The Atmospheric Composition Focus Area (ACFA; <https://science.nasa.gov/earth-science/programs/research-analysis/atmospheric-composition>) continues to provide quantitative global observations from space, augmented by suborbital and ground-based measurements of atmospheric aerosols and greenhouse and reactive gases enabling the national and international scientific community to improve our understanding of their impacts on climate and air quality. ACFA-sponsored research utilizes and coordinates advances in observations, data assimilation, and modeling to better understand the Earth as a system. Responding to both of the Earth Science Division (ESD)-relevant annual performance indicators, ACFA helped to gain insights into changes in the Earth's radiation balance, our prognostic capability for the recovery of stratospheric ozone and its impacts on surface ultraviolet radiation, and the evolution of greenhouse gases and their impacts on climate, as well as the evolution of tropospheric ozone and aerosols and their impacts on climate and air quality.

To demonstrate progress in **characterizing the behavior of the Earth system, including its various components and the naturally-occurring and human-induced forcings that act upon it**, ACFA sponsored research in FY2020 that aims to (a) more fully characterize space-borne measurements of aerosols and clouds in terms of the processes that impact the Earth's radiative flux, in particular the coupling between clouds and aerosols; (b) bridge the gap between the high temporal and spatial variability of air quality monitoring with a combination of new space-borne measurements well as expansion of ground-based networks; (c) understand the emissions of, for example, CO<sub>2</sub>, methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O), gases that persist in the atmosphere over time scales of a decade to centuries, with studies involving data from the NASA OCO-2 mission as well as OMI and TES on Aura together with key ground-based networks like AGAGE; (d) use NASA's portfolio of both space-based and suborbital observations for characterizing the evolution of the multi-decadal ozone recovery process, ongoing changes in radiative forcing, and provide the means to monitor compliance from the Montreal Protocol and its amendments; and (e) employ programmatic and Earth Venture (EV) class suborbital missions to reveal details of atmospheric processes ranging from trace gas emissions means to aerosol and cloud formations with higher accuracy and resolution than usually possible from space.

***A. Aerosol and cloud radiative effects research***

*The Emerging Technological Revolution in Earth Observations*

Stephens *et al.* (2020) highlighted NASA Earth observation advances in miniaturization. This revolution in part is associated with the emergence of CubeSat platforms that have forced a *de facto* standardization of the volume and power into which sensors have to fit. However, the extent to which small sensors can indeed provide similar or replacement capabilities compared to larger and more expensive counterparts has as yet barely been demonstrated. Moreover, any loss of capability of smaller systems weighed against the gains in costs and new potential capabilities offered by implementing them with a more distributed observing strategy has yet to be embraced. Their paper provides four examples of observations made with prototype miniaturized observing systems, including from CubeSats, that offer a glimpse of this emerging sensor revolution and a hint at future observing system design.

*Determining the daytime Earth radiative flux from DSCOVR*

Su *et al.* (2020) used observations from the National Institute of Standards and Technology Advanced Radiometer (NISTAR) onboard the Deep Space Climate Observatory (DSCOVR), which provides continuous full-disk global broadband irradiance measurements over most of the sunlit side of the Earth. The three active-cavity radiometers measure the total radiant energy from the sunlit side of the Earth in shortwave (SW; 0.2–4  $\mu\text{m}$ ), total (0.4–100  $\mu\text{m}$ ), and near-infrared (NIR; 0.7–4  $\mu\text{m}$ ) channels. The Level 1 NISTAR dataset provides the filtered radiances (the ratio between irradiance and solid angle). To determine the daytime top-of-atmosphere (TOA) shortwave and longwave radiative fluxes, the NISTAR-measured shortwave radiances were unfiltered with an algorithm developed for the NISTAR SW and NIR channels using a spectral radiance database calculated for typical Earth scenes. The resulting unfiltered NISTAR radiances were then converted to full-disk daytime SW and LW flux by accounting for the anisotropic characteristics of the Earth-reflected and emitted radiances. The anisotropy factors were determined using scene identifications determined from multiple low-Earth orbit and geostationary satellites as well as the angular distribution models (ADMs) developed using data collected by the Clouds and the Earth's Radiant Energy System (CERES). Su *et al.* found that global annual daytime mean SW fluxes from NISTAR were about 6 % greater than those from CERES, and both showed strong diurnal variations with daily maximum–minimum differences as great as 20  $\text{Wm}^{-2}$  depending on the conditions of the sunlit portion of the Earth. The NISTAR and CERES SW fluxes are also highly correlated, indicating that both capture the diurnal variation. Global annual daytime mean LW fluxes from NISTAR are 3% greater than those from CERES, but the correlation between them is only about 0.38.

*Detecting clouds and classifying thermodynamic phase using a machine-learning approach*

Wang *et al.* (2020) performed an investigation using a machine learning approach (Random Forest) to address passive imager classification problems for cloud detection and thermodynamic phase (*e.g.*, ice, liquid). Two concept models were developed for and

applied to SNPP VIIRS observations: an infrared-only model (8.6, 11, 12 $\mu$ m channels) applicable to both day and night conditions, and a daytime-only model (same IR channels plus the Near-IR and Shortwave-IR bands 0.86, 1.24, 1.38, 1.64, 2.25  $\mu$ m). Results were compared to both the standard MODIS (MOD35, MOD06) and the MODIS-VIIRS continuity (CLDMSK, CLDPROP) cloud products that use traditional thresholding approaches. The machine learning approach outperformed the heritage approaches (with respect to CALIOP) in the vast majority of cases.

#### Limited liquid-cloud-water response to anthropogenic aerosols

The response of liquid clouds to aerosols was investigated by Toll *et al.* (2019) using “pollution tracks” identified in global MODIS daytime reflectance imagery over a 15-year period. Pollution tracks, similar to ship tracks, are quasi-linear features within clouds downwind of known pollution sources (*e.g.*, smelters, oil refineries, etc.). MODIS (MOD06/MYD06) liquid water path (LWP) within and outside of pollution tracks is compared to assess the response of liquid clouds to aerosols. They found that the response of LWP to aerosol was relatively weak and due to offsetting effects on the optical thickness and droplet effective size (increased aerosol increases cloud droplet number concentration within clouds, both brightening the cloud and reducing droplet size). This finding of offsetting effects is similar to those obtained in ship track studies.

#### MODIS Dark-Target Algorithm Studies

The extended MODIS Dark-Target algorithm team continued to refine this ~20-year old product. Sawyer *et al.* (2020) described the release of a Dark Target aerosol optical depth (AOD) product for VIIRS and analyzed the differences between its results and those of MODIS Aqua. Differences between the MODIS and VIIRS instruments lead to some inevitable disagreement between their respective AOD measurements, but the offset between VIIRS SNPP and MODIS Aqua, which have similar orbits, is smaller than the offset between MODIS Aqua and MODIS Terra. The AOD record from VIIRS SNPP also agrees well with ground-based AOD measurements. For most purposes, Dark Target for VIIRS SNPP is consistent enough and in close enough agreement with MODIS to continue the record of satellite AOD beyond the expected lifespan of the MODIS instruments and into a time span long enough to use as a climate data record. Gupta *et al.* (2019) ported the Dark-Target algorithm to a new sensor, this time on a geosynchronous sensor (the Advanced Himawari Imager (AHI)). This first attempt showed overall good agreement with existing MODIS and AERONET data. However, there were some issues possibly related to geostationary having observing geometries unknown to polar-orbiting sensors. Overall, they see that there is at least some skill for a GEO satellite to observe the diurnal cycle of aerosol.

Sogacheva *et al.* (2020) approached the problem of characterizing global aerosol from a different perspective. Rather than trying to bridge different sensors with the same algorithm, the study attempted to find a path forward by using a wide variety of aerosol products from different international research groups and many different satellite sensors. The tried-and-true Dark Target aerosol algorithm plays an important role in this giant

merge. Finally, Zhou *et al.* (2020) looked at the Dark Target algorithm dust retrievals over oceans, which has been known to have problems. They solved this problem by using many different tests to ‘detect’ dust over ocean and then applied a non-spherical model (based on AERONET spheroid retrievals) to the detected dust. The result is improved retrieval of aerosol optical depth (AOD), spectral AOD and fine mode fraction.

*Investigation of CATS aerosol products and application toward global diurnal variation of aerosols*

Lee *et al.* (2019) presented a comparison of 1064 nm aerosol optical depth (AOD) and aerosol extinction profiles from the Cloud-Aerosol Transport System (CATS) level 2 aerosol product with co-located Aerosol Robotic Network (AERONET) AOD data, Moderate Imaging Spectroradiometer (MODIS) Dark Target AOD data from Aqua and Terra, and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) AOD and extinction data for the period of March 2015–October 2017. After quality-assurance checks of CATS data, reasonable agreement was found between aerosol data from CATS and other sensors. and for the first time, variations in AODs and aerosol extinction profiles were evaluated at 00, 06 12 and 18 UTC (and/or 00, 06, 12 and 18 local time or LT) on both regional and global scales. This study suggests that marginal variations are found in AOD from a global mean perspective, with the minimum aerosol extinction values found at 18 LT near the surface layer for global oceans, for both the June–November and December–May seasons. Over land, below 500 m, the daily minimum and maximum aerosol extinction values were found at 12:00 and 00/06 LT, respectively. Strong diurnal variations were also found over north Africa, the Middle East and India for the December–May season, and over north Africa, south Africa, the Middle East and India for the June–November season.

*The 4.4 km Multi-angle Imaging SpectroRadiometer (MISR) aerosol product*

Building upon the high quality of MISR’s version 22 (V22) 17.6-km resolution Aerosol Product and the results of numerous validation studies and feedback from the user community, the version 23 (V23) product increases the horizontal resolution to 4.4 km, streamlines the format and content, adds geolocation information and pixel-level uncertainty estimates, improves cloud screening, and provides a substantial increase in accuracy over oceans by implementing a correction for scattered light within the MISR cameras. Garay *et al.* (2020) describe the V23 product and evaluate its quality. It is publicly available from the NASA Langley Research Center Atmospheric Science Data Center.

***B. Air quality research***

*Abrupt decline in tropospheric nitrogen dioxide over China after the outbreak of COVID-19*

Liu *et al.* (2020) showed reductions in satellite measurements of nitrogen dioxide (NO<sub>2</sub>) pollution over China before and after the Lunar New Year (LNY). The observed

reduction in 2020 was ~20% larger than the typical holiday-related reduction and was related to changes in human behavior related to the outbreak of COVID-19. Nitrogen dioxide (NO<sub>2</sub>) is a measure of economic activity, as NO<sub>2</sub> is primarily emitted from fossil fuel consumption, and the authors related this NO<sub>2</sub> reduction not only to the imposition of provincial lockdowns but also to the reporting of the first of COVID-19 cases in each province that preceded the lockdowns. Both actions were associated with nearly the same magnitude of reductions.

*Comparison of Near-surface NO<sub>2</sub> Pollution with Pandora Total Column NO<sub>2</sub> During the Korea-United States Ocean Color (KORUS-OC) Campaign*

Thompson *et al.* (2020) examined near-surface air quality (AQ) observations over coastal waters off South Korea during the Korea-United States Ocean Color (KORUS-OC) Campaign in 2016. They noted that measurements of this type are scarce, a situation that limits our capacity to monitor pollution events at land-water interfaces. Satellite measurements of total column (TC) nitrogen dioxide (NO<sub>2</sub>) observations are a useful proxy for combustion sources, but the once-daily snapshots available from most sensors are insufficient for tracking the diurnal evolution and transport of pollution. Ground-based remote sensors like the Pandora Spectrometer Instrument (PSI) that have been developed to verify space-based TC NO<sub>2</sub> and other trace gases are being tested for routine use as certified AQ monitors. The KORUS-OC cruise aboard the R/V Onnuri in May-June 2016 represented an opportunity to study AQ near the South Korean coast, a region affected by both local/regional and long-distance pollution sources. Using PSI data in direct-Sun mode and *in situ* sensors for shipboard ozone, CO, and NO<sub>2</sub>, they explored for the first time relationships between TC NO<sub>2</sub> and surface AQ in this coastal region. Three case studies illustrate the value of the PSI and complexities in the surface-column NO<sub>2</sub> relationship caused by varying meteorological conditions. Case Study 1 (25-26 May 2016) exhibited a high correlation of surface NO<sub>2</sub> to TC NO<sub>2</sub> measured by both PSI and Aura's Ozone Monitoring Instrument, but two other cases displayed poor relationships between *in situ* and TC NO<sub>2</sub> due to decoupling of pollution layers from the surface. With suitable interpretation the PSI TC NO<sub>2</sub> measurement demonstrated good potential for working with upcoming geostationary satellites to advance diurnal tracking of pollution.

*Ceramic industry at Morbi as a large source of SO<sub>2</sub> emissions in India*

India's ceramic industry is an important source of anthropogenic SO<sub>2</sub> emissions that is not accounted for in common emissions inventories but can be estimated from satellite OMI SO<sub>2</sub> data. Using data from the Ozone Monitoring Instrument (OMI), Kharol *et al.* (2020) revealed a large sulfur dioxide (SO<sub>2</sub>) pollution "hotspot" over Morbi, Gujarat, India, attributing it to the ceramic industries in the area, and they estimated an upward pollution trend of ~300% between 2009 and 2016.. These new OMI emissions estimates can be used to monitor the impact of policy regulations to close Morbi-based ceramic units that are running on coal gasifiers.

*A Global Perspective on Wildfires from MISR observations*

Fire is part of the natural ecology of most vegetated settings, but wildland fire is also a major – and increasing – hazard in many populated regions of the world, to which recent severe fires in Australia, California, Indonesia, South America, and elsewhere attest. Aggressive fire suppression policies during much of the 20th century allowed fuel loads to grow artificially heavy, while settlements and agricultural enterprises progressively encroach on formerly pristine habitats. More broadly, shifting patterns of precipitation, lightning occurrence, and temperature in a changing climate are creating conditions that favor increasingly frequent and intense biomass burning, in ecosystems from boreal peatlands to tropical rain forests. Kahn (2020) presented a perspective on satellites provide global-scale data that are invaluable in efforts to understand, monitor, and respond to wildfires and emissions, which are increasingly affecting climate and putting humans at risk.

*Using TROPOMI NO<sub>2</sub> to estimate NO<sub>x</sub> from North American Cities and Power Plants*

Goldberg *et al.* (2019) used the TROPOspheric Monitoring Instrument (TROPOMI) to derive top-down NO<sub>x</sub> emissions for two large power plants and three megacities in North America. They first re-processed the vertical column NO<sub>2</sub> with an improved air mass factor to correct for a known systematic low bias in the operational retrieval near urban centers. For the power plants, top-down NO<sub>x</sub> emissions agree to within 10% of the emissions reported by the power plants. They then compared their estimates of NO<sub>x</sub> emissions rates for New York City, Chicago, and Toronto to projected bottom-up emissions inventories. In their analysis of 2018 NO<sub>x</sub> emissions, they found a +22% overestimate for New York City, a –21% underestimate in Toronto, and good agreement in Chicago in the projected bottom-up inventories when compared to the top-down emissions. Top-down NO<sub>x</sub> emissions also capture intraseasonal variability, such as the weekday-versus-weekend effect (emissions are +45% larger on weekdays versus weekends in Chicago). Finally, they demonstrated the enhanced capabilities of TROPOMI, which allow us to derive a NO<sub>x</sub> emissions rate for Chicago using a single overpass on July 7, 2018. The large signal-to-noise ratio of TROPOMI is well-suited for estimating NO<sub>x</sub> emissions from relatively small sources and for sub-seasonal timeframes.

*Long-term exposure to PM<sub>2.5</sub> and incidence of disability among the oldest old*

Lv *et al.* (2020) evaluated the association of fine particulate matter (PM<sub>2.5</sub>) exposure and incidence of disability in carrying out activities of daily living (ADL) in a cohort of more than 15,000 individuals aged 80 years and older in China. The Dalhousie University global PM<sub>2.5</sub> dataset generated from NASA MODIS, MISR, and SeaWiFS aerosol data was geolocated with residential addresses of the study participants. Risk magnitude was found to significantly increase above 33 µg/m<sup>3</sup>, with each 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> exposure corresponding to a 7.7% increase in the risk of disability in ADL. The study concludes that air pollution reduction will mitigate the public health burden of disability and increase the quality of life of older adults, particularly men, smokers, and people with cognitive impairment.

***C. Tropospheric greenhouse and other trace gas research***

*Improved estimates of biospheric carbon balance from OCO-2 satellite retrievals*

The Orbiting Carbon Observatory 2 (OCO-2) is NASA's first satellite dedicated to monitoring CO<sub>2</sub> from space and could provide novel insight into CO<sub>2</sub> fluxes across the globe. However, one continuing challenge is the development of a robust retrieval algorithm: an estimate of atmospheric CO<sub>2</sub> from satellite observations of near-infrared radiation. The OCO-2 retrievals have undergone multiple updates since the satellite's launch, and the retrieval algorithm is now on its ninth version. Some of these retrieval updates, particularly version 8, led to marked changes in the CO<sub>2</sub> observations, changes of 0.5 ppm or more. Miller and Michalak (2020) evaluated the extent to which current OCO-2 observations can constrain monthly CO<sub>2</sub> sources and sinks from the biosphere, and they particularly focus on how this constraint has evolved with improvements to the OCO-2 retrieval algorithm. They found that improvements in the CO<sub>2</sub> retrieval are having a potentially transformative effect on satellite-based estimates of the global biospheric carbon balance. The version 7 OCO-2 retrievals formed the basis of early inverse modeling studies using OCO-2 data; these observations are best equipped to constrain the biospheric carbon balance across only continental or hemispheric regions. By contrast, newer versions of the retrieval algorithm yield a far more detailed constraint, and they are able to constrain CO<sub>2</sub> budgets for seven global biome-based regions, particularly during the Northern Hemisphere summer when biospheric CO<sub>2</sub> uptake is greatest. Improvements to the OCO-2 observations have had the largest impact on glint-mode observations, and they also find the largest improvements in the terrestrial CO<sub>2</sub> flux constraint when they include both nadir and glint data.

*Assessing Measurements of Pollution in the Troposphere (MOPITT) carbon monoxide retrievals over urban versus non-urban regions*

The Measurements of Pollution in the Troposphere (MOPITT) retrievals over urban regions have not been validated systematically, even though MOPITT observations are widely used to study CO over urban regions. Tang *et al.* (2020) compared MOPITT products over urban and non-urban regions with aircraft measurements from several recent airborne field missions. In general, MOPITT agreed reasonably well with the *in situ* profiles over both urban and non-urban regions. Version 8 multispectral product (V8J) biases vary from -0.7 % to 0.0 % and version 8 thermal-infrared product (TIR) biases vary from 2.0 % to 3.5 %. The evaluation statistics of MOPITT V8J and V8T over non-urban regions are better than those over urban regions with smaller biases and higher correlation coefficients. They found that the agreement of MOPITT V8J and V8T with aircraft measurements at high CO concentrations is not as good as that at low CO concentrations, although CO variability may tend to exaggerate retrieval biases in heavily polluted scenes. They tested the sensitivities of the agreement between MOPITT and *in situ* profiles to assumptions and data filters applied during the comparisons of MOPITT retrievals and *in situ* profiles. The results at the surface layer were insensitive to the model-based profile extension (required due to aircraft altitude limitations), whereas those at levels with limited aircraft observations (*e.g.*, the 600 hPa layer) were more sensitive to the model-based profile extension. Daytime MOPITT products have smaller overall biases than nighttime MOPITT products when comparing both MOPITT daytime

and nighttime retrievals to the daytime aircraft observations. However, it would be premature to draw conclusions on the performance of MOPITT nighttime retrievals without nighttime aircraft observations. Applying signal-to-noise ratio (SNR) filters did not necessarily improve the overall agreement between MOPITT retrievals and in situ profiles, likely due to the reduced number of MOPITT retrievals for comparison. Comparisons of MOPITT retrievals and *in situ* profiles over complex urban or polluted regimes are inherently challenging due to spatial and temporal variabilities of CO within MOPITT retrieval pixels (*i.e.*, footprints). They demonstrated that some of the errors are due to CO representativeness with these sensitivity tests, but further quantification of representativeness errors due to CO variability within the MOPITT footprint will require future work.

*Interpreting volcanological processes in Kamchatka from multi-sensor satellite observations*

Volcanoes are complex environmental systems that pose challenges to scientific study, due to their inherently hazardous nature and in many cases, remote locations. Satellite-based remote sensing provides a useful tool for assessing both ongoing activity and retrospective eruptions. Flower and Kahn (2019) presented an initial application of a multi-sensor approach, in part to demonstrate its strengths and limitations in a single volcanic region that is fairly well monitored *in situ*. They utilized data from five NASA satellite-based instruments with up to 18 years of global observations to conduct in-depth investigations of eight volcanoes on the Kamchatka Peninsula (Russia) that were active between 2000 and 2018. From 169 eruptive plumes observed, they performed detailed plume-dynamics analysis in eighty-two cases for which sufficiently favorable observations were obtained. Plume heights from MISR and CALIOP, microphysical particle properties (e.g. fine ash, sulfates) from MISR, thermal anomalies generated by lava features from MODIS, and sulfur dioxide (SO<sub>2</sub>) concentrations from OMI and OMPS were all considered. Evidence of eruption evolution over months-to-years was identified at Shiveluch, Kliuchevskoi, Kizimen, Karymsky, Zhupanovsky, Koryaksky and Kambalny. In cases with extensive data coverage (Kliuchevskoi, Kizimen, Karymsky and Zhupanovsky), underlying subsurface dynamics were inferred and corroborated where possible with detailed ground-based data records. The 1.1 km resolution of the particle-property retrievals from the Multi-angle Imaging SpectroRadiometer (MISR) instrument captured downwind plume-particle evolution in many cases. Comparison of changes in aerosol optical depth (AOD), retrieved effective particle size (REPS) and retrieved effective particle absorption (REPA) mapped to six plume transport regimes, indicating varying degrees of downwind particle aggregation, deposition, and/or new particle formation. Distinct meteorological conditions were identified as likely driving these evolutionary processes, most notably the atmospheric static stability and wind shear at plume altitude. This approach can be applied to volcanic plumes globally, including those for which surface monitoring is limited or entirely absent.

*Assessing Methods to Derive Ammonia Emissions Over North America Using Synthetic Observations*

Li *et al.* (2019a) evaluated two inverse modeling methods for deriving ammonia emissions in experiments with the GEOS-Chem chemical transport model and its adjoint. They simulated synthetic ammonia (NH<sub>3</sub>) column density as observed by the Cross-track Infrared Sounder (CrIS) over North America to test the ability of the iterative finite-difference mass-balance (IFDMB) and the four-dimensional variational assimilation (4D-Var) methods to recover known NH<sub>3</sub> emissions. Comparing to the more rigorous 4D-Var method, the IFDMB approach requires 3–4 times lower computational cost and yields similar or smaller errors (12–17% vs 17–26%) in the top-down inventories at 2° × 2.5° resolution. When directly conducting inversions at 0.25° × 0.3125°, the IFDMB consistently exhibits larger errors (44–69% vs 30–45%) than the 4D-Var approach. Applying inversion results at 2° × 2.5° to update the a priori emissions at 0.25° × 0.3125° could improve the accuracy of IFDMB inversions and reduce the computational cost of 4D-Var.

#### ***D. Upper atmospheric and ozone depletion research***

##### *Record-low Arctic stratospheric ozone in 2020: MLS observations of chemical processes and comparisons with previous extreme winters*

During the boreal winter/spring of 2019/2020, the Arctic stratospheric polar vortex experienced an early onset and a sustained presence of the cold conditions conducive to the microphysical and chemical processes that result in chlorine-catalyzed ozone loss. These same processes give rise to the Antarctic "ozone hole", and a study by Manney *et al.* (2020) used observations from the Microwave Limb Sounder (MLS) on NASA's Aura mission to show that, during 2019/2020, the chemical composition of the Arctic polar vortex evolved in a more Antarctic-like manner than typical, leading to the lowest Arctic ozone values ever observed in the lower stratosphere.

##### *Australian PyroCb Smoke Generates Synoptic-Scale Stratospheric Anticyclones*

During a particularly intense period in the Australian 2019/2020 fire season, an outbreak of powerful thunderstorms fueled by very strong bushfires in southeast Australia emitted unprecedented amounts of water vapor, smoke, and other pollutants to heights 16 km above the surface. Kablick *et al.* (2020) used observations from NASA's Microwave Limb Sounder (MLS), NASA's Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), and the NOAA Ozone Mapping and Profiler Suite (OMPS) to show that the plume subsequently rose from the lowermost stratosphere (15–16 km) to altitudes above 31 km in less than 2 months. Model calculations shows that solar heating of the very dark plume drove this rapid ascent, creating a temperature anomaly - with colder air above the plume and warmer air below - along with an anticyclonic circulation that helped maintain the coherence of the plume over this period.

##### *Validation of SAGE III/ISS Solar Occultation Ozone Products with Correlative Satellite and Ground-Based Measurements*

The Stratospheric Aerosol and Gas Experiment III on the International Space Station (SAGE III/ISS) was launched on 19 February 2017 and began routine operation in June 2017. The first two years of SAGE III/ISS (v5.1) solar occultation ozone data were evaluated by Wang *et al.* (2020) using correlative satellite and ground-based measurements. Of the three SAGE III/ISS retrieved solar ozone products (MES, AO3, and MLR), AO3 ozone shows the smallest bias and best precision, with mean biases less than 5% for altitudes ~15–55 km in the midlatitudes and ~20–55 km in the tropics. In the lower stratosphere and upper troposphere, AO3 ozone shows high biases that increase with decreasing altitudes and reach ~10% near the tropopause. Preliminary studies indicate that those high biases primarily result from the contributions of the oxygen dimer (O<sub>4</sub>) not being appropriately removed within the ozone channel. The precision of AO3 ozone is estimated to be ~3% for altitudes between 20 and 40 km. It degrades to ~10–15% in the lower mesosphere (~55 km) and ~20–30% near the tropopause. There could be an altitude registration error of ~100 m in the SAGE III/ISS auxiliary temperature and pressure profiles. This, however, does not affect retrieved ozone profiles in native number density on geometric altitude coordinates. In the upper stratosphere and lower mesosphere (~40–55 km), the SAGE III/ISS (and SAGE II) retrieved ozone values show sunrise/sunset differences of ~5–8%, which are almost twice as large as what was observed by other satellites or model predictions. This feature needs further study.

#### ***E. Airborne and surface-based activities***

##### *Atmospheric Carbon and Transport-America (ACT-America)*

Pal *et al.* (2020) provided the first documentation of the structure of CO<sub>2</sub> and CH<sub>4</sub> across frontal boundaries and as a function of altitude using measurements from the ACT-America 2016 summer field experiment. This study provides benchmark metrics of greenhouse gas weather that can be used to evaluate the atmospheric transport and carbon flux simulations that in turn are used to interpret long-term atmospheric carbon observations and to conduct atmospheric inverse flux estimates. In another paper, Barkley *et al.* (2019) showed that methane emissions from the multiple oil and gas production regions found in the south-central United States are roughly twice as large as estimated in current EPA emissions inventories, while agricultural methane emissions are roughly in agreement with EPA inventories. To distinguish between these two major methane sources they employed an innovative dual-tracer technique as well as ethane-to-methane emission ratios for the methane sources. They also demonstrated a new, weather-informed technique for solving for emissions from a large region. By flying across frontal boundaries, ACT-America aircraft were able to sample emissions from the entire south-central region of the United States at one time. The results also disprove the hypothesis that discrepancies between inventories and aircraft data are caused by a daytime sampling bias in the aircraft measurements, since these flights were sampling emissions from one to two days prior to the time of the flights.

##### *Observations of Aerosols above Clouds and their interactions (ORACLES)*

ORACLES was a five-year investigation with three Intensive Observation Periods (IOP) designed to study key processes that determine the climate impacts of African biomass burning (BB) aerosols. Shinozuka *et al.* (2019) developed a framework for evaluating the performance of a range of global and regional aerosol models against observations made during the ORACLES airborne mission in September 2016. They found that six models typically place the bottom of the smoke layer at lower altitudes than do the airborne lidar observations by 300–1400 m, whereas model aerosol top heights are within 0–500 m of the observations. Extinction coefficients in the free troposphere (FT) and above-cloud aerosol optical depth (ACAOD) are 10–30 % lower in WRF-CAM5, 30–50 % lower in GEOS-5, 10–40% higher in GEOS-Chem, 10–20 % higher in EAM-E3SM except for the practically unbiased 3–6 km extinction, and 20–70 % lower in the Unified Model, than the airborne *in situ*, lidar and sunphotometer measurements. This study highlights a new approach to utilizing airborne aerosol measurements for model diagnosis.

#### ***F. International Activities***

##### *Committee on Earth Observation Satellites Atmospheric Composition Virtual Constellation*

The Committee on Earth Observation Satellites (CEOS) was established in 1984 to coordinate civil space-borne observations of the Earth. Participating agencies strive to enhance international coordination and data exchange and to optimize societal benefit. Currently, 52 members and associate members made up of space agencies, national, and international organizations participate in CEOS planning and activities.

In support of the Group on Earth Observations (GEO) objectives and as a space component of the Global Earth Observation System of Systems (GEOSS), CEOS has developed the concept of virtual, space-based Constellations. A Constellation is a coordinated set of space and/or ground segment capabilities from different partners that focuses on observing a particular parameter or set of parameters of the Earth system.

The CEOS Atmospheric Composition Virtual Constellation (AC-VC) goal is to collect and deliver data to improve monitoring, assessment and predictive capabilities for changes in the ozone layer, air quality and climate forcing associated with changes in the environment through coordination of existing and future international space assets.

The AC-VC chairs are from ESA, NASA, and NIES-Japan, and many NASA researchers are involved in its diverse activities. In the past year, its Greenhouse Gas (GHG) Roadmap and Project will implement the three-step approach recommended in the AC-VC GHG white paper, *A Constellation Architecture for Monitoring Carbon Dioxide and Methane from Space*<sup>1</sup> (160+ pages) endorsed by CEOS leadership at its 2018 Plenary. This activity was led by David Crisp at JPL. AC-VC continues to contribute to the implementation of activities defined in the Roadmap.

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<sup>1</sup> [http://ceos.org/document\\_management/Virtual\\_Constellations/ACC/Documents/CEOS\\_AC-VC\\_GHG\\_White\\_Paper\\_Publication\\_Draft2\\_20181111.pdf](http://ceos.org/document_management/Virtual_Constellations/ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Publication_Draft2_20181111.pdf)

## Management and Performance: FY 2020 Annual Performance Report

The 2019 CEOS Plenary endorsed the white paper AC-VC authored *Geostationary Satellite Constellation for Observing Global Air Quality: Geophysical Validation Needs*<sup>2</sup>. AC-VC is coordinating implementation of the three most immediate recommendations expressed in the “GeoAQ” white paper.

AC-VC is undertaking a new coordination activity for aerosol observations from space with application to air quality, an important topic for which no other international coordination activity currently exists. Particular consideration will be given to synergies with the next-generation operational GEO imagers. AC-VC is currently producing a survey document on this activity.

Website: <http://ceos.org/acc>

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<sup>2</sup> [http://ceos.org/document\\_management/Virtual\\_Constellations/ACC/Documents/GEO AQ Constellation Geophysical Validation Needs 1.1 2Oct2019.pdf](http://ceos.org/document_management/Virtual_Constellations/ACC/Documents/GEO_AQ_Constellation_Geophysical_Validation_Needs_1.1_2Oct2019.pdf)

### **Section 1.1.8.2 Carbon Cycle and Ecosystems Focus Area**

NASA research in the Carbon Cycle and Ecosystems focus area continues to increase knowledge of the changes in Earth's biogeochemical cycles, ecosystems, land cover, and biodiversity. Sub-orbital and satellite observations are used to detect and quantify these changes and, when used within numerical simulation models, to improve our ability to assess impacts, identify feedbacks, and predict future changes and consequences for society. The research is a balance between local, regional and global studies, with local studies providing insight into important processes that elucidate the region's unique role in the Earth system. Quantification of biogeochemical processes are contributing to improved satellite algorithms for implementation into modeling activities. Selected research results and other accomplishments of the 2020 fiscal year are highlighted below.

Contributions from the Carbon Cycle and Ecosystems Focus area to Annual Performance Indicator 1.1.8 provided new insights into coastal, marine, and terrestrial ecosystem structure (biomass, canopy cover), function (interactions between drought and fire, (e.g., in the US Midwest), coastal particulate organic carbon), and composition (diel vertical movement of marine animals, biodiversity). This information is quantified using lidar data from ship-based, field studies, airborne and satellite retrievals from local (e.g., plots in Gabon, Africa) to regional (e.g., the southern Gulf of Maine, Alaskan arctic and boreal forests, Amazon, Indonesian peats, northern high latitudes) to global scales.

#### ***Ocean Biology and Biogeochemistry***

New applications of both satellite-and-ship-mounted light-detection-and-ranging (lidar) instruments continue to advance the current understanding of ocean biology. Collister et al. (2020) utilized a ship-based lidar to examine calcite-rich waters associated with a coccolithophore bloom in the southern Gulf of Maine. The authors found that lidar measurements were able to inform about the nature and abundance of particles suspended in coastal waters, and helped improved satellite algorithms, particularly improving quantification of particulate inorganic carbon (PIC) remotely. Behrenfeld et al. (2020) utilized ten years of data from the cloud-aerosol lidar with orthogonal polarization (CALIOP) sensor to better understand global distributions of diel vertical migration (DVM), a poorly constrained, yet well known behavior of several marine animals. DVM is thought to be primarily an adaptation to avoid visual predators in the sunlit surface layer, and consists of daily excursions where animals migrate hundreds of metres to the surface at night, feed on plankton, and then return to depths of 200-1000m where they reside during the day. While DVM has been measured acoustically from ships for decades, CALIOP data enabled, for the first time, a global picture of this migration. The authors found that there were some areas in the ocean, such as subtropical gyres, where there was a larger fraction of migrators; the time series also revealed significant temporal trends in DVM biomass, and correlated variations in DVM biomass and surface productivity. This remarkable migration was also recently observed using optical measurements from Bio-Argo floats, a network of profiling robots that sample the ocean from the surface to 2000m continuously at hundreds of locations daily (Haentjens et al., 2020). This is the first time this network of profilers is used to detect migrating organisms, a method which could prove tremendously valuable to study animals that

migrate over extended time scales and in remote areas not easily accessible by ships. These results provide important insight on biological and biogeochemical activities, and a path forward for improving our understanding of the ocean as a whole.

The EXport Processes in the Ocean from Remote Sensing (EXPORTS; Siegel et al., 2016) project is collecting critical information for quantifying the export and fate of upper ocean net primary production using satellite observations and state of the art ocean technologies. The project completed its first successful field campaign in the North Pacific in 2018, where the team gathered a wealth of data on ocean biogeochemistry, ecosystem function, and physical forcings, and how each of the different components of the Biological Carbon Pump (BCP) are linked and contribute to carbon export. Some of the work that is undergoing seeks to elucidate the contribution of different size particles to the diet of zooplankton, which are significant contributors to the carbon flux. For example, the work done by Romero-Romero et al. (2020) in the Equatorial Pacific suggests that small particles constitute between 9% and 98% of zooplankton diets, being the contribution higher at sites with lower flux regimes. EXPORTS is using the same techniques as this work, and the improved understanding of carbon export under different productivity regimes that will result from this project is expected to help better constrain how climate-driven changes in primary production will in turn impact export of particles throughout the water column.

Light emerging from natural water bodies contains information about the constituents of the water, as well as (depending on the depth), the type of ocean bottom, whereas light penetration is important for marine ecosystems such as coral reefs. Hochberg et al. (2020) characterized the spectral diffuse attenuation coefficient ( $K_d$ ) in coral reef and adjacent waters of Hawaii and Bermuda, and found that the suspended sediments on coral reef flats and in lagoons (mostly calcium carbonate) has the effect of increasing the overall magnitude of  $K_d$ . The authors also found that reefs generate large amounts of dissolved organic matter, which help protect them from UV radiation. These data provide some insight into reef water clarity and color and their importance to reef ecology. Light also impacts a variety of ecosystem functions, such as phytoplankton growth. Using data from the North Atlantic Aerosol and Marine Ecosystem Study (NAAMES), Morison et al. (2020) examined the important role of light on phytoplankton growth and zooplankton grazing rates. Their results suggest that light could be a potential tool to predict the relative dynamics of phytoplankton growth and grazing losses, especially in large areas of the ocean. These data provide insights into predator-prey processes and their effects on spatio-temporal dynamics of phytoplankton biomass, and such predictive capability would be essential for enhancing ocean food web functions.

In the coming years, an increase in spectral resolution in satellite and airborne remote sensing missions is expected, which will lead to new or improved capabilities for characterizing aquatic ecosystems. Two such missions include the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission and the Surface Biology and Geology (SBG) designated observable mission. In preparation to these missions, the scientific community is already developing aquatic remote sensing data product algorithms that will be able to capitalize on the wealth of information these new sensors will provide. Casey et al.

(2019) put together an organized dataset of geographically diverse, quality-controlled, high spectral resolution inherent and apparent optical property (IOP–AOP) aquatic data which will constitute the foundation of such algorithm development, and will also be critical to perform calibration and validation activities for forthcoming aquatic-focused imaging spectrometry missions. These carefully curated datasets are critical to ensure the generation of high quality, high fidelity satellite products for scientific and application use.

### ***Terrestrial Ecology***

#### *Vulnerability and Resilience of Northern Ecosystems*

High latitude regions contain some of the most rapidly changing and vulnerable ecosystems on Earth. New analyses from the Arctic Boreal Vulnerability Experiment (ABoVE) have allowed better understanding of how key ecological properties are changing across space and time, and how these changes will impact the Earth system. Feedbacks from changing Arctic and boreal ecosystems accelerate climate change through carbon releases from thawing permafrost and higher solar absorption from reductions in Earth surface albedo, following loss of sea ice and land snow.

Arctic and boreal ecosystems play an important role in the global carbon (C) budget, and whether they act as a future net C sink or source depends on the feedbacks between ecosystems and a changing climate. Liu et al., 2019 used *in situ* measurements, model simulations, and satellite observations to investigate the climatic and environmental controls on seasonal exchange of carbon dioxide (CO<sub>2</sub>) during an anomalously warm winter in 2015 and 2016. They found that for a warm spring, photosynthesis was enhanced more than respiration, leading to greater CO<sub>2</sub> uptake. However, photosynthetic enhancement from spring warming was partially offset by greater ecosystem respiration during the preceding anomalously warm winter, resulting in nearly neutral effects on the annual net CO<sub>2</sub> balance. This study demonstrates the critical need for year round continuous measurements to capture antecedent conditions and other drivers of carbon emissions.

Indeed, warming in the Arctic is causing permafrost soils, which represent the largest terrestrial organic carbon pool (1330–1580 Gt) on Earth to decompose more rapidly, even during winter. A recent study by Natali et al. (2019) demonstrated that winter CO<sub>2</sub> release from permafrost soils (resulting from microbial decomposition) was significantly greater than the uptake of CO<sub>2</sub> by plant during the growing season, suggesting that the Arctic region is a source of carbon.

#### *Forest Structure*

New LiDAR remote sensing missions such as the Global Ecosystem Dynamics Investigation (GEDI) and Ice, Cloud and land Elevation Satellite 2 (ICESat-2) are beginning to provide robust measurements of forest structure at Global scales. Simulation studies have demonstrated that GEDI data can be leveraged to characterize multiple components of forest structure including canopy cover (Tang et al., 2019) and biomass (Duncanson 2020) at global scales. These GEDI based structure measurements can be leveraged to gain a better understating of biodiversity within forested ecosystems (e.g., Burns et al., 2020 and Marselis et al., 2020). Although ICESat-2 is

optimized for cryosphere studies it also collects forest structure data which can be leveraged to develop estimates of forest biomass (Narine et al., 2020). These new missions will facilitate the development of novel global forest biomass products in the coming decade.

#### *Human Impacts on Terrestrial Ecosystems*

Human activities can also have large impacts on ecosystems and associated biogeochemical cycles, especially when coupled with natural processes. For example, for the Amazon rainforest, which plays a critical role in the Earth's climate system, Bullock et al. (2020) leveraged a time series of Landsat satellite data to map deforestation, degradation, and natural disturbance from 1995 to 2017. They found that the area of disturbed forest in the Amazon is 44–60% more than previously realized, indicating an unaccounted for source of global carbon emissions and more pervasive damage to forest ecosystems in the Amazon.

In another study, Goldberg et al. (2020) also used Landsat time series data (2000–2016) to map the drivers of mangrove forest loss, one of the most carbon dense ecosystems on the planet, across the globe. They estimated that 62% of global mangrove losses between 2000 and 2016 resulted from land-use change, primarily through conversion to aquaculture and agriculture, and that up to 80% of these human-driven losses occurred within six Southeast Asian nations, reflecting the regional policy of enhancing aquaculture for export to support economic development. Human activity has also had significant impacts on tropical peat swamp forests (PSFs), another carbon dense ecosystem. According to Wedeux et al. (2020), 35% of peatlands have been drained and converted to plantations in Southeast Asia, and much of the remaining forest had been logged, contributing significantly to global carbon emissions. However, since tropical forests have the capacity to regain biomass quickly and forests on drained peatlands may grow faster in response to soil aeration, the net effect of humans on forest biomass remains poorly understood. Wedeux et al. (2020) used repeat LiDAR surveys to map forest biomass in 2011 and 2014 across peat swamp forests in Kalimantan, Indonesia. By comparing these results with carbon flux measurements, they found that carbon sequestration in above-ground biomass growth offset roughly half of the carbon efflux from peat oxidation.

#### *SIF as an Indicator of Ecosystem Function*

Recent advances in satellite remote sensing of solar-induced fluorescence (SIF) are promising for estimating gross primary production (GPP), with emerging capability in space-based methodologies and various possibilities for applications. Although previous studies have demonstrated that SIF offers a strong potential for monitoring photosynthesis at local, regional, and global scales, the relationships between photosynthesis and SIF on diurnal and seasonal scales are not fully understood. Campbell et al. (2019) examined how fine spatial and temporal scale SIF observations relate to leaf level chlorophyll fluorescence metrics and canopy gross GPP. They found positive linear relationships between SIF and canopy GPP as well as SIF and leaf electron transport rate (an indicator of photosynthetic activity), demonstrating that

canopy SIF metrics are able to capture the dynamics in photosynthesis at both leaf and canopy levels.

SIF is also showing promise for large-scale characterization and monitoring of crop productivity. For example, He et al. (2020) used tower-based SIF measurements and process modelling to explore the relationships between the gross primary production (GPP) or crops and SIF. They found linear relationships between GPP and SIF for C4 crops (e.g., corn), while the relationship shows some saturation for C3 crops (e.g., soybean) at high light levels. They also demonstrate that satellite SIF measurements from the TROPospheric Monitoring Instrument (TROPOMI) were correlated with ground based GPP observations. County-level TROPOMI SIF observations were also strongly correlated with crop productivity. In another study, Yin et al. (2020) also used SIF measurements from TROPOMI to quantify the impact of large scale floods on cropland productivity in the US Midwest. They found that, due to delayed crop planting caused by a large scale flood, there was a 16-day shift in the seasonal cycle of photosynthesis relative to 2018, along with a 15% lower peak value. Further they estimated a reduction of 0.21 PgC in cropland gross primary productivity in June and July, which was partially compensated for by an increase in productivity during August and September (+0.14 PgC). These studies highlight the potential of SIF for reliable crop monitoring at regional to global scales.

### ***Land Cover and Land Use Change***

#### *United States*

Quantifying variation in ecosystem function provides novel insights into the temporal dynamics of changing importance of multiple resources to ecosystem function. Water- and light resource-use loading factors are coherent at annual timescales. Based on the results from 7 sites of eddy covariance data during the 2009-2017 period and maintenance respiration use efficiency (mRUE) factors for a site in the US Midwest (Kalamazoo River Watershed), Reed et al. (2020) reported declining patterns of carbon use efficiency by a loading factor, highlighting the ecosystem's trade-off between carbon uptake and respiration during the growing season. At annual and monthly timescales, the influence decreases (from ~ 85% to ~ 65%) for loading factors for carbon use, while influence of light use loading factors peaks to ~ 60% at growing season timescales.

Bolton et al. (2020) described a continental-scale land surface phenology algorithm and data product based on harmonized Landsat 8 and Sentinel-2 (HLS) imagery. The algorithm creates high quality times series of vegetation indices from HLS imagery, which are then used to estimate the timing of vegetation phenophase transitions at 30 m spatial resolution. Results from assessment efforts evaluating Land Surface Phenology retrievals, and provide examples illustrating the character and quality of information related to land cover and terrestrial ecosystem properties provided by the continental dataset. The algorithm is highly successful in ecosystems with strong seasonal variation in leaf area (e.g., deciduous forests). Importantly, the MS-LSP data product was made publicly available on the Land Processes Distributed Active Archive Center (LP DAAC) in early 2020.

### *Northern Eurasia*

Composite tree-ring series from northern Eurasia for spruce and pine contain a major fraction of decadal and multidecadal variability. The most likely driver of this common variability is interannual to multidecadal climate variability. The most consistent pattern emerged for spruce at all but the southernmost area. Hughes et al. (2020) reported that cool and moist summers the year before growth were consistent drivers of spruce ring growth throughout the period, with no change in recent decades. The specific role of moisture variability in determining interannual to multidecadal variability in tree growth in this high latitude region raises questions about the relative vulnerability of spruce and pine under global warming.

In another Northern Eurasia study, three factors that alter N availability—permafrost degradation, atmospheric N deposition, and the abandonment of agricultural land to forest regrowth (land-use legacy). Kicklighter et al., (2019) reported simulated carbon storage in forest vegetation over the 21<sup>st</sup> century within the context of two IPCC global-change scenarios (Representative Concentration Pathway (RCPs) 4.5 and 8.5). For RCP4.5, which is a mitigation scenario that peaks in the mid 21<sup>st</sup> century and declines model results suggested enhanced N availability results in increased tree carbon storage of 27.8 Pg C, with land-use legacy being the most important factor. For RCP8.5, which is a no mitigation scenario, enhanced N availability results in increased carbon storage in trees of 13.4 Pg C, with permafrost degradation being the most important factor. Analysis reveals complex spatial and temporal patterns of regional carbon storage. This study underscores the importance of considering carbon-nitrogen interactions when assessing regional and sub-regional impacts of global change policies.

### *Northern Eurasia Workshops in Land Cover, Land Use Change*

Conservation of Arctic Flora and Fauna (CAFF) released a proceedings report for two workshops held during Arctic Science Summit Weeks in Prague (2017) and Arkhangelsk (2019) included recording and monitoring arctic plant-community diversity and distributions, wildlife habitat studies, and modelling the changes in the structure and function of the vegetation as the arctic climate changes. <https://caff.is/proceedings-series/492-arctic-vegetation-archive-and-arctic-vegetation-classification-proceedings-and-a>:

### ***Biodiversity***

#### *Biodiversity Impacts from a Changing Climate*

Advances in remote sensing have allowed for new means of detecting biological diversity across the globe. For instance, Marselis et al. (2019) tested the ability of airborne LIDAR data products to predict tree species richness and diversity measures gathered from four study sites in Gabon. They found that canopy height predicted 44% of richness and 43% of diversity and adding vertical canopy structure further improved the predictive capability to 71% for both dependent variables. The modeling results are encouraging in the context of developing pan-tropical structure-diversity models applicable to data from current and upcoming spaceborne remote sensing missions. Bell et al. (2020) simulated the ability of a spaceborne hyperspectral imager to accurately map fractional cover of coral reef benthic classes. While accuracy varied with depth and chlorophyll or sediment

concentration, the study indicates that repeat measurements of a hyperspectral satellite will produce more accurate and useful fractional cover data across broad conditions. Chirayath et al. (2019) used a combination of new fluid lensing and MiDAR data in concert with a machine learning technology and citizen science classification to build a system capable of mapping coral reef ecosystem makeup globally at unprecedented spatial and temporal scales.

Rapid advances in the collection of in situ data paired with remote sensing open the possibility for radical new understanding of the Earth system processes that govern the distribution of biological diversity. For instance, in-situ wildlife observations have become increasingly available through the creation of tools to manage, process and analyze camera trap records (Ahumada et al. 2020). Environmental DNA (eDNA) analysis allows the simultaneous examination of organisms across multiple trophic levels and domains of life, providing critical information about the complex biotic interactions related to ecosystem change. Using an eighteen-month (2015–2016) time-series of seawater samples from Monterey Bay, California, Djurhuus et al. (2020) identified the presence of 663 taxonomic groups ranging from microorganisms to mammals. This data allowed monitoring of changes in the composition of communities, putative interactions among taxa, and correlations between these communities and environmental properties. In-situ recordings of ambient sound paired with remotely sensed observations of light at night have enabled a framework to detect the presence of ‘sensory danger zones’, hotspots of conservation concern where sensory pollutants overlap in space and time with an organism’s activity (Dominoni et al. 2020).

Use of remote sensing in ecological studies continues to enable new insights. For instance, Braun et al. (2019) found that sharks leverage swirling ocean vortices (mesoscale eddies) as a means of diving and foraging in deeper waters. Combining shark movement data gathered through satellite-transmitters and remotely sensed observations of sea surface height variation, the authors quantified specific shark–eddy interactions. This predator dives deep in warm, swirling water masses called warm-core (anticyclonic) eddies as a conduit to forage in the deep ocean that contains the largest fish biomass on Earth. Wilson et al. (2019) combined remote sensing and in situ observations to explain the massive phytoplankton growth following the 2018 eruption Kilauea Volcano. Lava-impacted seawater contained high concentrations of nutrients brought to the surface ocean when heat from the substantial input of lava into the ocean warmed nutrient-rich deep waters and caused them to rise. It is possible that this mechanism has led to similar ocean fertilization events in the past. Razenkova et al. (2020) used MODIS derived indices of vegetation productivity (Dynamic Habitat Indices) to accurately predict moose population abundance from 1981 – 2010 in Russia. Model performance significantly decreased following the collapse of the Soviet Union, suggesting the influence of secondary variables (increased human hunting pressure) may be responsible.

This capability has never been more necessary as impacts of climate change on global biodiversity continues to mount. For instance, Santora et al. (2020) found that unprecedented 2014–2016 northeast Pacific marine heatwaves led to a record numbers of whale entanglements in the central California Current crab fishery. Leveraging sea

surface temperature reanalysis products, the authors determined the heat wave led to habitat compression of coastal upwelling and changes in availability of forage species, driving whale foraging shoreward. This was exacerbated in 2016, when domoic acid contamination prompted fishery delays and intensified the spatial overlap between whales and crab fishery gear. Zhu et al. (2019) found that warming global temperatures will lead to functionally colder winters for many animal species who rely on sub-snow habitat for winter shelter. Using land surface freeze/thaw status and snow cover products, the authors found that since 1980 average snow-covered days decreased by 18 day. By 2100, snow covered days will decrease an additional 16 days threatening species dependent on sub-snow environments to survive low temperatures.

These effects are paired with an unprecedented rate of direct human impact on the environment. Massive deforestation rates continue across the globe. In the Chaco biodiversity hotspot of South America, machine learning classification of Landsat and Sentinel data show illicit crops and alluvial mining are responsible for 60% of the 2000+ km<sup>2</sup> forest loss that has occurred since 2001 (Anaya et al, 2020). In the Congo Basin of Central Africa, Landsat data reveal since 2003 the total length of logging road networks has increased by nearly doubled. Deforestation rates have more than doubled along active roadways, particularly in areas outside of managed logging concessions (Kleinschroth et al. 2019). Plastics and other artificial materials pose new risks to health of the ocean. Anthropogenic debris travels across large distances and is ubiquitous in the water and on the shorelines, yet, observations of its sources, composition, pathways and distributions in the ocean are very sparse and inaccurate. van Sebille et al. (2020) outline the need for an integrated observing system that leverages multiple remote sensing technologies to detect and track this growing environmental threat.

### **Section 1.1.8.3 Climate Variability and Change Focus Area**

Research supported by NASA's [Climate Variability and Change](#) (CVC) focus area increases our knowledge of global climate and sea level on seasonal to multidecadal time scales, by focusing on the individual and interactive climate processes occurring in the ocean, atmosphere, land and ice. Through a wide range of disciplinary and interdisciplinary projects, CVC supports the evaluation and utilization of satellite, aircraft and ground-based observations of the global ocean, sea and land-based ice, land surface and atmosphere, as well as their integration into comprehensive, interactive Earth system models and assimilation systems. These activities can be divided into those focused on characterizing the behavior of the Earth system (performance indicator 1.1.8), and those that focus on enhanced understanding and prediction (performance indicator 1.1.9).

It is useful to break the supported activities into four major categories:

- Sea Ice in the Climate System
- Land Ice in the Climate System
- Oceans in the Climate System
- Earth System Modeling

Highlights of results published this past year related to the characterization of the behavior of the Earth system relevant to the CVC FA are summarized below:

#### **Sea Ice in the Climate System**

Sea ice plays a critical role in the Earth system by both reflecting solar radiation and regulating the transfer of heat and momentum between the atmosphere and ocean. NASA continues to study sea ice and its interactions with other components of the Earth System using a number of space-based measurements.

Sea ice extent and other Arctic sea ice properties and trends are reported routinely by NASA through the Arctic Sea Ice News & Analysis (ASINA) website hosted by the National Snow and Ice Data Center (NSIDC) (<http://nsidc.org/arcticseaicenews/>) and through the support of researchers that contribute to NOAA's Arctic Report Card (<http://www.arctic.noaa.gov/Report-Card>). The ASINA website continues to be a primary reference for researchers, the media, and the general public.

Significant papers were published in the last year using ICESat-2 to study sea ice properties, its thickness, and changes. Petty et al. (2020) generated the first sea ice thickness product from ICESat-2. Differences between their February/March 2019 thickness estimates and ICESat February/March (19 February to 21 March) 2008 ice thickness estimates using the same input assumptions, show an ~0.37 m or ~20% thinning across an inner Arctic Ocean domain in this 11-year time period. Comparisons with various monthly sea ice thickness estimates obtained from European Space Agency's CryoSat-2 satellite mission showed consistently lower thickness estimates from ICESat-2

however. Additionally, for the first time ever, ICESat-2 provided Arctic-wide sea ice heights during the summer (Kwok et al., 2020). In the 2019 summer, area-averaged freeboard decreased from 34 cm prior to melt to a minimum of 12 cm in August, along with a coincident area-averaged albedo decreased from ~0.7 to 0.38. Calculations using ICESat-2 freeboards and modeled ice thickness from Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) give area-averaged snow depths ranging from 17 cm prior to melt to 3 cm in August over seasonal ice and from 34 to 4 cm over multiyear ice. Mean rates of snow ablation (including evaporation) in mid-June were as high as 2 cm/day, comparable to field records from other years. Increases in freeboard after mid-August in the high latitude (>80°N) multiyear ice cover, north of the Greenland coast, are likely due to earlier freeze-up and snow accumulation in these regions with shorter melt seasons.

Schweiger et al. (2019) produced a sea ice reconstruction for the 1901 – 2010 period by forcing the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) with ERA-20C atmospheric data. They compare the magnitude and patterns of sea ice variability between the first half of the twentieth century (1901–40) and the more recent period (1980–2010), both marked by sea ice decline in the Arctic. The first period contains the so-called early-twentieth-century warming (ETCW; ~1920–40) during which the Atlantic sector saw a significant decline in sea ice volume, but the Pacific sector did not. The sea ice decline over the 1979–2010 period is pan-Arctic and 6 times larger than the net decline during the 1901–40 period. Sea ice volume trends reconstructed solely from surface temperature anomalies are smaller than PIOMAS-20C, suggesting that mechanisms other than warming, such as changes in ice motion and deformation, played a significant role in determining sea ice volume trends during both periods.

For the Antarctic sea ice, Parkinson (2019) completed a 40-y record of satellite observations to quantify changes in Antarctic sea ice coverage since the late 1970s. The satellite record reveals that a gradual, decades-long overall increase in Antarctic sea ice extents reversed from 2014 to 2017. While we saw a record high yearly average in 2014 of 12.8 Million km<sup>2</sup>, the rapid decreases reduced the Antarctic sea ice extents to their lowest values in the 40-y record, both on yearly average basis (record low in 2017) and on a monthly basis (record low in February 2017). Still, when considering the 40-y record as a whole, the Antarctic sea ice continues to have a positive overall trend in yearly average ice extents of  $11,300 \pm 5,300$  km<sup>2</sup>/yr. Four of the 5 sectors into which the Antarctic sea ice cover is divided all also have 40-y positive trends. The one anomalous sector in this regard, the Bellingshausen/Amundsen Seas, has a 40-y negative trend, with the yearly average ice extents decreasing overall in the first 3 decades, reaching a minimum in 2007, and exhibiting an overall upward trend since 2007 (i.e., reflecting a reversal in the opposite direction from the other 4 sectors and the Antarctic sea ice cover as a whole).

### **Land Ice in the Climate System**

The Ice sheet Mass Balance Intercomparison Exercise (IMBIE) Team compared and combined regional climate model outputs with 26 individual satellite measurements of changes of the Greenland Ice Sheet volume, flow and gravitational potential to produce a reconciled estimate of its mass balance (IMBIE Team, 2019). The ice sheet was close to a state of balance in the 1990s, but annual losses have risen since then, peaking at  $345 \pm 66$  billion tons per year in 2011. In all, Greenland lost  $3,902 \pm 342$  billion tons of ice between 1992 and 2018, causing the mean sea level to rise by  $10.8 \pm 0.9$  millimeters. Using three regional climate models, they show that the reduced surface mass balance (net snowfall after melting and other sources of ablation) has driven  $1,964 \pm 565$  billion tons half of the ice loss owing to increased meltwater runoff. The remaining  $1,938 \pm 541$  billion tons half of ice loss was due to increased glacier dynamical imbalance, which rose from  $46 \pm 37$  billion tons per year in the 1990s to  $87 \pm 25$  billion tons per year since then. The total rate of ice loss slowed to  $222 \pm 30$  billion tons per year between 2013 and 2017, on average, as atmospheric circulation favored cooler conditions and ocean temperatures fell at the terminus of Jakobshavn Isbræ. Cumulative ice losses from Greenland as a whole have been close to the rates predicted by the Intergovernmental Panel on Climate Change for their high-end climate warming scenario, which forecast an additional 70 to 130 millimeters of global sea-level rise by 2100 compared with their central estimate.

ICESat-2 data were used to provide significant new insight into the behavior and trends of ice sheets. For example, Smith et al. (2020) provide unified estimates of grounded and floating ice mass change from 2003 to 2019 from ICESat-2 data. Their analysis reveals patterns likely linked to competing climate processes: Ice loss from coastal Greenland (increased surface melt), Antarctic ice shelves (increased ocean melting), and Greenland and Antarctic outlet glaciers (dynamic response to ocean melting) was partially compensated by mass gains over ice sheet interiors (increased snow accumulation). Losses outpaced gains, with grounded-ice loss from Greenland (200 billion tons per year) and Antarctica (118 billion tons per year) contributing 14 millimeters to sea level. Quantifying changes in Earth's ice sheets and identifying the climate drivers are central to improving sea level projections.

Year-round meltwater drainage from Greenland was documented by Pitcher et al. (2020). They found evidence of runoff during winter, ~4 months after summer melt. Ground-penetrating radar and borehole surveys in the proglacial Isortoq River reveal slowly flowing water beneath river ice >0.5 m thick. Geochemical analysis of this water indicates previous contact with the ice sheet bed. Comparable surveys in proglacial rivers draining four neighboring catchments found no winter drainage, despite a brief surface melt event ~10 days prior. They conclude that the ice sheet bed can stay wet and drain small amounts of meltwater year-round. This study provides the first direct evidence of continuous wintertime residual meltwater drainage, confirming the existence of a wet bed and live subglacial hydrological system year-round for at least some parts of the ice sheet.

For Antarctica, Morlighem et al. (2020) presented a novel, high-resolution and physically based description of Antarctic bed topography using mass conservation constrained by data collected during NASA's decade-long IceBridge program. Their results reveal

previously unknown basal features with major implications for glacier response to climate change. The Antarctic Ice Sheet has been losing mass over past decades through the accelerated flow of its glaciers, conditioned by ocean temperature and bed topography. Glaciers retreating along retrograde slopes (that is, the bed elevation drops in the inland direction) are potentially unstable, while subglacial ridges slow down the glacial retreat. Despite major advances in the mapping of subglacial bed topography, significant sectors of Antarctica remain poorly resolved and critical spatial details are missing.

The Morlighem et al data was used by Brancato et al. (2020) who in combination with satellite radar interferometry from the COSMO-SkyMed constellation detected a  $5.4 \pm 0.3$  km grounding line retreat of the Denman Glacier in Antarctica between 1996 and 2017–2018. Denman Glacier, East Antarctica, holds an ice volume equivalent to a 1.5 m rise in global sea level. The bed topography indicates that the retreat proceeds on the western flank along a previously unknown 5 km wide, 1,800 m deep trough, deepening to 3,400 m below sea level. On the eastern flank, the grounding line is stabilized by a 10 km wide ridge. At tidal frequencies, the grounding line extends over a several kilometer-wide grounding zone, enabling warm ocean water to melt ice at critical locations for glacier stability. If warm, modified Circumpolar Deep Water reaches the sub-ice-shelf cavity and continues to melt ice at a rate exceeding balance conditions, the potential exists for Denman Glacier to retreat irreversibly into the deepest, marine-based basin in Antarctica.

Bed topography is also particularly important for determining where water flows accumulate, but digital elevation models of the ice sheet bed rely on interpolation and are unrealistically smooth, biasing estimates of subglacial lake location and surface area. Antarctic subglacial lakes can play an important role in ice sheet dynamics, biology, geology, and oceanography, but it is difficult to definitively constrain their character and locations. Subglacial lake locations are related to factors including heat flux, ice surface slope, ice thickness, and bed topography, though these relationships are not fully quantified. To address this issue, MacKie et al. (2019) use geostatistical methods to simulate realistically rough bed topography. They used their simulated topography to predict subglacial lake distribution across the continent using a binomial logistic regression, which uses physical parameters and known lake locations to calculate the probabilities of lake occurrences. Their results suggest that topography models interpolated without appropriate geostatistics overestimate subglacial lake surface area and that total lake surface area is lower than previously predicted. Ice-penetrating radar-detected lakes are more likely to occur in the interior of East Antarctica, while altimetry-detected (active) lakes are expected to be found more often in West Antarctica and near the grounding zone. They observed that radar-detected lakes have a high correlation with heat flux and ice thickness, while active lakes are associated with higher ice velocity.

**ITS\_LIVE (Inter-mission Time Series of Land Ice Velocity and Elevation)** is a new NASA MEaSURES project to provide automated, low latency, global glacier flow and elevation change datasets (<https://its-live.jpl.nasa.gov>). The project aims to provide glacier and ice sheet surface velocities from all Landsat 4/5/7/8 and Sentinel-2 a/b optical and all Sentinel-1 a/b SAR images using a single workflow, processed on an identical

grid, provided in an identical data format and processes and distributed from the cloud. In addition to velocities, ITS\_LIVE is producing synthesized records of Antarctic and Greenland elevation change from ERS 1/2, Envisat, CryoSat-2 and ICESat 1/2 and Antarctic ice shelf ocean melt rates all provided on a grid compatible with the ITS\_LIVE velocity products. The continuous multi-parameter data stream will help researchers characterize the underlying mechanisms that link Earth's ice to its atmosphere and ocean. The NASA MEaSUREs ITS\_LIVE scene-pair velocity data set is now available online at NASA Jet Propulsion Laboratory, eight million individual scene-pairs cover all the permanent ice-covered areas larger than 5 km<sup>2</sup>, globally. It spans 1984 to early 2019 and has a spatial resolution of 240 m.

### **Oceans in the Climate System**

Oceans play a fundamental role in the Earth's system, modulating our planet's climate and weather by storing and transporting large quantities of heat, water, moisture, and carbon dioxide, as well as exchanging these elements with the atmosphere. This continuous exchange of properties influences climate and weather patterns over the globe by releasing the heat that fuels the overlying atmospheric circulation, releasing aerosols that impact cloud cover, absorbing and storing atmospheric carbon dioxide for millennia, and by releasing moisture that determines the fate of the global hydrological cycle. NASA's Physical Oceanography Program supports a wide range of studies that quantify the ocean's role in the climate system by utilizing remote and in situ observations, numerical models and data assimilating systems. The program supports research that characterizes both ocean's intrinsic variability, its dynamics and thermodynamics, as well as ocean's interactions within the complex ocean-atmosphere-land-solid Earth system. Below are most notable discoveries in 2019-2020 that advanced our understanding of the ocean's role in the climate system.

#### ***Ocean dynamics as a regulator of Earth's heat budget***

Oceans have an important role in the Earth's energy imbalance. Due to its large heat capacity, which exceeds that of the atmosphere over 1000 times, the oceans have absorbed most of the heat gained by the planet in response to anthropogenic greenhouse gas emissions, delaying the full consequences of the atmospheric warming. A classic depiction of ocean heat transport is often viewed through a concept of large-scale ocean conveyor belt, indicating that water flows between remote regions circulating warm water and heat around the globe. However, a new study by Forget and Ferreira (2019) challenges the classic concept, suggesting that these global-scale seawater pathways may play less of a role in Earth's heat budget than previously thought. The study uses NASA's state-of-the-art estimates of ocean heat transport based on the most recent ECCO solution (Estimating the Circulation and Climate of the Ocean) and emphasizes that it is the divergence or convergence of heat transport within an oceanic region, rather than the origin or destination of seawater transiting through that region, that is most immediately relevant to Earth's heat budget. The results reveal that the net ocean heat redistribution takes place primarily within oceanic basins and to a lesser extent through exchanges between basins. In particular, Forget and Ferreira (2019) demonstrate the overwhelming

predominance of the tropical Pacific in distributing heat across the globe, from the equator to the poles, which exports four times as much heat as is imported in the Atlantic and Arctic Oceans. In contrast to the classic great conveyor belt concept, the study emphasizes the importance of the Pacific Ocean in the Earth's heat budget, giving a new perspective on the net 'effective' ocean heat transport within the coupled climate system.

Increasing evidence suggests measurable changes in ocean circulation in response to greenhouse warming. The change in ocean circulation exhibits diverse geographical variations, ranging from strong intensification in the tropical Pacific, which was in part responsible for a recent climate warming hiatus (e.g., England et al., 2014), to weakening of the Gulf Stream related to the change of the Atlantic Overturning Meridional Circulation, as suggested by recent theoretical (Johnson et al., 2019) and observational studies (Frajka-Williams et al., 2019). Regional changes in ocean circulation and transport are often influenced by complex internal dynamics and thus strong internal variability. Therefore, unlike for sea level or surface temperature, the issue of assessing a trend in global-mean ocean circulation as a convenient metric of climate change has always been a challenge. This year, a new study by Hu et al. (2020) was able to demonstrate the occurrence of a substantial acceleration of global mean ocean circulation over the past two decades. The study uses the output of the ECCO solution and other reanalysis, models, and in situ observations to compute the total global integral of kinetic energy, which is used as an index for measuring the intensity of the ocean circulation (i.e., a measure of the usable energy for the movement of seawater). Their results demonstrate a statistically significant increasing trend in the globally-integrated oceanic kinetic energy since the early 1990s. The rate of change is equivalent to an increase of  $15\pm 12\%$  decade over the climatological mean. The acceleration in the global mean ocean circulation is deep-reaching (deeper than 1000 m) and particularly prominent in the tropical oceans. It can be potentially attributed to the planetary intensification of surface winds since the 1990s. The magnitude of the acceleration exceeds those associated with natural variability, suggesting the influence of a long-term anthropogenic trend.

### ***Ocean expansion and sea level rise***

Rising seas is a well-documented consequence of warming climate (e.g., IPCC, 2013). Rising seas are among the most disruptive consequences of climate change, impacting highly-populated coastal communities, ecosystems, and national and global economy, threatening America's trillion-dollar coastal property market and public infrastructure (e.g., USGCRP, 2018) and potentially exposing up to 300 millions of people to risks of sea level rise and coastal flooding by 2050 (e.g., Kulp and Strauss, 2019).

While the global-mean sea level is often the focus of the general public and a commonly-used indicator of a climate change of many studies, including most recent NASA's work by Frederikse et al. (2020), it is the regional and local sea level that are most relevant to the humanity, presenting major threats to coastal communities in forms of flooding, erosion, storm surge, and wave setups. To improve our understanding of regional sea level changes and advance our capabilities to predict its future changes, NASA leads a multi-disciplinary collaboration among ocean physicists, cryospheric scientists,

geodesists, and hydrologists through the NASA Sea Level Change Science Team (N-SLCT; <https://sealevel.nasa.gov>).

A major milestone of N-SLCT activities this year was the completion of a comprehensive review study (Hamlington et al., 2020) that untangles complex physics of sea level change by quantifying how individual physical mechanisms contribute to rising seas, and how these processes combine and vary geographically over the globe. The study represents NASA's collective knowledge about the current state of understanding of regional sea level variations associated with the ocean thermodynamics, which arise from both natural and anthropogenic contributions, vertical land motion near the coasts, changes in ice mass of the ice sheets and glaciers, and variability in land water storage and redistribution of land ice and water. Given its high societal and economic relevance, the study also discusses higher-frequency sea level variability associated with tides, storm surges, ocean swell, and wave setup. Combined, the study presents updated estimates of major components of the regional sea level budget and their relevant time scales and potential magnitudes. Readers can assess the degree to which each physical process needs to be accounted for within any particular time frame of interest, with the impacts ranging from millimeters on yearly time scales from changing ice sheets to meters of sea level change induced by ocean processes. Another unique contribution of the review is a discussion of areas where the lack of understanding or gaps in knowledge inhibit our ability to assess future changes in sea level, as well as the role of the expanded sea level observation network that can improve our collective knowledge of sea level science. The discussion of knowledge gaps and uncertainties is expected to be useful to those translating NASA's science into actionable plans and solutions for policy- and decision-makers.

### ***Oceans role in the Earth's freshwater budget***

Observational and modeling studies suggest that the Earth water cycle is undergoing significant changes over the past half century in response to the warming climate, manifested by the increased moisture content in the atmosphere, increased evaporation and higher frequency of heavy rain events. Being the largest source of freshwater and global moisture supplier, including the moisture that falls as land precipitation, oceans are in the center of the changing water cycle story, including its pattern amplification and trends. The recent study by Yu et al. (2020) provides updated evidence of rapid intensification of the ocean water cycle based on various satellite observations and reanalysis products. The results show positive linear trends in both evaporation (E) and precipitation (P) over the global ocean in response to the warming climate over the past 30 year-period. Spatial patterns in the difference between E-P (i.e., the water cycle) show intensification of the tropical rainfall regions in both Pacific and Atlantic ITCZs (Inter-Tropical Convergence Zones), and the expansion towards the equator of the subtropical dry zones, confirming predicted 'dry gets drier and wet gets wetter' paradigm, albeit with a spread around theoretical ( $\sim 7^\circ \text{C}^{-1}$ ) estimates based on the Clausius-Clapeyron relationship.

The exchange of freshwater between E, P, and runoff leaves a strong imprint on ocean salinity. Given the availability of accurate salinity measurements over the globe,

including those provided by remote sensing missions from Aquarius and SMAP missions, the use of salinity to fingerprint the changes in the water cycle is emerging a practical alternative of satellite-derived rainfall and evaporation estimates, and one of the foci of the NASA Ocean Salinity Science Team. Over the years, the use of salinity information as a proxy of the amplified water cycle has evolved from a simple response to the changes in E-P, which is often obscured by the upper-ocean circulation and mixing, to more sophisticated approaches that take into account conservation principles and water mass transformation theory. In particular, Yu et al. (2020) reports how a new method based on water mass transformation theory and salinity information can be used to determine the amount of change in the water cycle. Estimates using surface salinity measurements suggest that the global water cycle had amplified by  $8\% \pm 5^\circ \text{C}^{-1}$  of global mean surface temperature rise since 1950s (see also Skliris et al. (2016) and Zika et al. (2018) for earlier studies).

### **Earth System Modeling**

Models supported by the Modeling, Analysis and Prediction (MAP) program within the Climate Variability and Change focus area include, but are not limited to the following:

- The NASA GISS Model E, an Earth system model which is utilized for multidecadal studies of the climate system and understanding the various anthropogenic and natural factors influencing global change on decadal to multidecadal time scales.
- The GEOS Modeling System, which includes the GEOS modular Earth system model, the GEOS data assimilation system, the GEOS coupled chemistry/climate model, and the GEOS chemistry and transport model.
- The NASA Unified WRF model, which is directed toward developing a comprehensive representation of the Earth system at regional scales.
- The Estimating the Climate and Circulation of the Ocean (ECCO) assimilation system, jointly supported by the Physical Oceanography and MAP components of the CVC focus area. Its goal is to generate an accurate, high resolution, coupled ocean/sea ice/biogeochemistry atmospherically-consistent state estimate for research applications and prediction.

Results from studies utilizing these and other MAP supported modeling efforts focused on characterization of the behavior of the Earth system included:

### ***Climate modeling advances***

Recent efforts to improve solar heating codes in climate models have focused on more accurate treatment of the absorption spectrum or fractional clouds. However, a mostly forgotten assumption in climate models is that of a flat Earth atmosphere, an assumption that could bias climate models by an amount comparable to the radiative forcing difference between preindustrial times and the present. Prather and Hsu (2019) address this problem by introducing simple fixes to the current flat Earth climate models.

Work to improve and extend the NASA GISS model continues with a major update. Kelley et al. (2020) describes a new GISS-E2.1 version, which is being used to contribute to the Coupled Model Intercomparison Project, Phase 6 (CMIP6). This model version differs from the predecessor model (GISS-E2) chiefly due to parameterization improvements to the atmospheric and ocean model components. Model skill is significantly higher than in previous versions. In particular, there have been specific improvements in representations of modes of variability (such as the Madden-Julian Oscillation and other modes in the Pacific) and significant improvements in the simulation of the climate of the Southern Oceans, including sea ice.

Properly representing boundary-layer convection in global climate models presents a major modeling challenge. Suselj et al. (2019) describe a fully unified parameterization of boundary layer and moist convection that treats both shallow and deep convection. The new parameterization is based on the stochastic multiplume eddy-diffusivity/mass-flux (EDMF) approach, which distinguishes between convective plumes and nonconvective mixing. The new parameterization was tested in a single-column model against large-eddy simulations (LESs) for cases representing weakly precipitating marine convection and the diurnal cycle of continental deep convection. The results of these EDMF experiments compare well with the LES reference simulations. In particular, the transitions between the different dominant convection regimes were realistically simulated.

### ***Clouds and cloud process modeling advances:***

At temperatures between 0 °C and approximately -37 °C, clouds can exist as both liquid and ice. The fraction of condensate that remains liquid depends among other things on the presence of certain materials being immersed within, or in contact with the cloud droplets, known as ice nucleation particles. Since in a cloud the particles impacting each droplet may differ in size and composition, they may induce freezing at slightly different temperatures. It has been difficult to account for this variation when estimating the rate of ice formation in a cloud. Barahona (2020) develops for the first time a method to deal with the problem, which will improve estimates of cloud droplet freezing in climate models.

### ***Chemistry/climate modeling advances***

Understanding the role of atmospheric chemistry in the climate system requires implementation of an atmospheric chemistry scheme in climate models, but this represents a major computational challenge due to the large number of reactions and the stiffness (the presence of very short characteristic time constants which require a small step size for numerical stability) of the system. To address this challenge, Shen et al. (2020) describe an adaptive method to greatly reduce the cost of the chemistry in climate models while maintaining high accuracy. A set of 20 reduced chemical mechanisms to cover the range of atmospheric conditions were constructed, and then a decision is made “on the fly” to pick which mechanism to use for a given grid box and time step on the basis of computed production and loss rates for individual species. Results from a 2-year

GEOS-Chem simulation shows that the method can reduce the computational cost of chemical integration by 30 %–40 % while maintaining accuracy better than 1 % and with no error growth. (GEOS-Chem is a community-developed standalone chemistry and transport model which is also integrated within the NASA GEOS Modeling system supported by the CVC FA).

***Land and land/atmosphere coupling advances***

Severe and persistent 21st-century drought in southwestern North America (SWNA) raises questions about the role played by anthropogenic climate change. Williams et al. (2020) used hydrological modeling and new 1200-year tree-ring reconstructions of summer soil moisture to demonstrate that the 2000–2018 SWNA drought was the second driest 19-year period since 800 CE, exceeded only by a late-1500s megadrought. The megadrought-like trajectory of 2000–2018 soil moisture was driven by natural variability superimposed on drying due to anthropogenic warming. Anthropogenic trends in temperature, relative humidity, and precipitation estimated from 31 climate models account for 47% (model interquartiles of 35 to 105%) of the 2000–2018 drought severity, pushing an otherwise moderate drought onto a trajectory comparable to the worst SWNA megadroughts since 800 CE.

### **Section 1.1.8.4 Earth Surface and Interior Focus Area**

NASA's Earth Surface and Interior focus area (ESI) continues to advance the understanding of core, mantle, and lithospheric structure and dynamics, and interactions between these processes and Earth's fluid envelopes. Research conducted in the past year has also provided the basic understanding and data products needed to inform the assessment and mitigation of natural hazards, including earthquakes, volcanic eruptions, and landslides. ESI's Space Geodesy Program (SGP) continues to produce observations that refine our knowledge of Earth's shape, rotation, orientation, and gravity, foundational to many Earth missions and location-based observations. The ESI strategy is founded on the seven scientific challenges identified in the *Challenges and Opportunities for Research in ESI (CORE) Report* (Davis et al, 2016, <http://go.nasa.gov/2hmZLQO>): 1. [Plate boundaries], 2. [Tectonics and surface processes], 3. [Solid Earth and sea level], 4. [Magmatic systems], 5. [Deep Earth], 6. [Magnetic field], and 7. [Human impact]. The ESI chapter summarizes highlighted accomplishments of the past year that respond to addressing these seven *CORE* challenges. Below are highlights of ESI Focus Area funded research accomplishments that have matured over the past year and represent research that has been funded over the past several ROSES cycles. Referenced ESI publications are also archived on [ESDpubs](#).

The scope of NASA's Earth Surface and Interior focus area (ESI) falls largely under the 1.1.8 "characterizing the behavior of the Earth system" performance goal. This includes the observation, analysis, and interpretation of any Earth surface or interior property or process using satellite, airborne, or associated ground instruments, along with computational and other assessment tools. Publications under this category contribute to improving interpretations of primarily space-based and remote sensing observations, identifying and addressing noise and other error sources, as well as the ability to characterize features related to the earth surface and interior, such as mineral mapping, identifying earthquake deformation and source properties, and determining the presence of fluctuations in gravity and/or the electromagnetic field.

### **Lithospheric Processes**

Lithospheric structure and dynamics, and interactions between these processes and the oceans, hydrologic system, and atmosphere are critical to understanding the Earth system. This includes the motion and rotation of tectonic plates, elastic properties of the crust and mantle, and the effects of surface loading resulting from surface water, ground water, other fluids, glaciers, and ice sheets. Hydrogeodesy continues to emerge as a growing field of study, with important advancements in understanding connections between natural and anthropogenic fluid flux and solid-Earth deformation. The contribution of vertical land motion to rates of relative sea level rise continues to be a major insight provided by ESI research. Many of these studies also represent enabling research for the hazards advancements and satellite mineral mapping described in the following section.

## Hydrogeodesy

Advances of space geodesy over the past decade have enabled transformative research progress in the rapidly evolving field of hydrogeodesy. Space-based observations and advanced geodetic techniques (e.g., GRACE-FO, GPS, InSAR) and groundwater level records can be combined to identify and understand interactions between hydrologic and solid-Earth processes. Six of the seven science challenges identified in the *CORE Report* either directly address water as a signal source or the need to mitigate the effect of water in the geodetic time-series to advance our understanding of the science. Investigation of these challenges helps bring us closer to understanding how natural and anthropogenic changes in water shapes solid-Earth processes.

InSAR data were used by Gapenthin et al, (*Water Resources Research*, 2019) to measure surface deformation responses to known amounts of drawdown, recovery, and management over 25 non-continuous years at the Buckman well field in Santa Fe, New Mexico. This study demonstrated the complexity of directly relating surface deformation induced by groundwater production and the need for data relating to geothermal gradients and local stratigraphy.

California's Central Valley, one of the world's most productive agricultural regions that is highly dependent on groundwater resources, experienced a drought from 2012 to 2015 that has been the subject of study for several publications utilizing GRACE and InSAR data. Liu et al., (*Geoscience*, 2019) used both GRACE and Sentinel-1 InSAR data to monitor groundwater resources following the drought from March 2015 to May 2017 and found continued pumping-induced subsidence. They also found a close temporal correlation in subsidence events and groundwater anomaly variation from GRACE, demonstrating the utility of satellite geodesy in tracking groundwater storage change. Using GRACE data Ojha et al., (*Journal of Hydrology*, 2020) demonstrated that the central valley aquifer system did not reach equilibrium during the drought and may be experiencing delayed compaction of the aquitard, adding to the amount of subsidence observed after the drought. Chaussard and Farr (*Geophys. Res. Lett.*, 2019) looked at InSAR data from 2019 in the Central Valley to identify elastic (recoverable) and inelastic (permanent) deformation occurring in the aquifer to develop sustainable pumping practices. They used independent component analysis to isolate expressions of elastic deformation and found that, contrary to previous research, an elastic deformation component can be found in both seasonal and long-term multi-seasonal drawdown.

## Solid-Earth Contributions to Relative Sea Level Change

The contribution of vertical land motion to rates of relative sea level rise continues to be a major insight provided by ESI research. Improved models of relative sea level rise incorporate geodetic techniques (i.e., InSAR, GPS, and lidar), to characterize both localized and regional natural and anthropogenic coastal subsidence/uplift; and gravity field measurements from GRACE, monitoring sea level change and ice mass balance. This year, Blackwell et al., (*Science Advances*, 2020) combined InSAR and GNSS measurements to characterize vertical land motion along the California coastline to a

submillimeter scale and found that anywhere from 4.3 to 8.7 million people in this area are exposed to subsidence and have an increased amount of relative sea-level rise.

### **Mineral Mapping**

Using image spectroscopy techniques, satellite sensors acquiring imagery in the VNIR, SWIR, and TIR wavelengths are able to determine surface compositions. By applying these methods to the Earth's surface, researchers are able to remotely map the location of minerals. Kumar et al., (*Int. J. Appl. Earth Obs Geoinformation*, 2020) applied a machine learning algorithm to AVIRIS-NG hyperspectral data acquired over Hutti, India to automate this process and was able to accurately map several different mineral contacts. In coastal areas, these mapping techniques can be challenging due to turbid backscatter, atmospheric aerosols, and sun glint off the water surface. Thompson et al., (*Remote Sensing of Environment*, 2019) resolved these issues by developing a retrieval method that adapts the optimal estimation formalism to coastal domains. With this method they found that mineral maps of coastal areas acquired from both PRISM and AVIRIS-NG matched in situ validation measurements.

## **Natural Hazards Research**

New and innovative natural hazards research and analysis is providing insights into understanding risk from earthquakes, volcanic eruptions, and landslides. This includes assessments of processes underlying seminal events, as well as developments in monitoring. Recent studies have focused on the Ridgecrest earthquake and tsunamis. Four of the seven *CORE* challenges are specific to Natural Hazards research [1. Plate boundaries, 2. Tectonics and surface processes, 4. Magmatic systems, and 7. Human impact].

### **Earthquakes**

Both optical WorldView and InSAR imagery can be used to characterize the surface deformation resulting from earthquakes. Gold et al., (*Geophys. Res. Lett.*, 2019) used high resolution WorldView optical imagery validated by field and InSAR observations to quantify vertical surface deformation associated with the 20 May 2016 Mw 6.0 Peterman Ranges earthquake. The study demonstrated the potential for using optical imagery for quantifying modest (<1 m) vertical deformation.

On 4 July 2019 a sequence of major earthquakes occurred near Ridgecrest, California, ending a nearly 20-year hiatus in major earthquake activity in southern CA. Ross et al., (*Science*, 2019) used geodetic, seismic, and seismicity data to map the complex fault geometry relating to this sequence for the first time and identified how well modern instrumentation and analysis techniques can be used to quantify regional seismic hazards.

## **Tsunamis**

Tsunamis are known to be triggered by seismic waves of large earthquakes occurring near the ocean as well as seismicity from volcanic eruptions and water displacement from landslides. Ulrich et al., (*Pure Appl. Geophys.*, 2019) applies physics-based modeling techniques to optical and InSAR geodetic data to identify how the Mw 7.5 Palu-Koro strike-slip earthquake triggered an unexpected localized tsunami. They identified that the trigger for this tsunami was likely related entirely to submarine earthquake displacement, not landsliding. This provides insight into tsunamis triggered on strike-slip faults worldwide.

Tsunamis can also affect the Earth's gravity field. Ghobadi-Far et al., (*Journal of Geodesy*, 2020) observed transient gravity perturbations using GRACE from the 2004 Sumatra, 2010 Maule, and 2011 Tohoku tsunamis. These data are complementary to those gathered by buoys, ocean bottom pressure sounders, and satellite altimeters, and this study demonstrates an innovative way of applying GRACE data to transient geophysical mass changes.

## **Volcanoes**

Owing to practical limitations, especially at remote or heavily vegetated volcanoes, less than half of Earth's 1400 subaerial volcanoes have ground monitoring and fewer are monitored consistently. Thus, current and future Earth-observing satellite missions, with global and frequent measurements of volcanic activity, are critical.

Combining data from multiple sensors often provides additive and complimentary information that helps the community to better understand and monitor volcanic activity. Flower and Kahn, (*Remote Sensing of Environment*, 2020) provided a new combination of using multi-sensor data for volcano monitoring by incorporating TIR data from MODIS to identify thermal anomalies, UV data from OMI and OMPS to track SO<sub>2</sub> plumes, LiDAR data from CALIOP and multi-angle VNIR data from MISR to observe volcanic ash and aerosol properties occurring from 2000 to 2018 on the Kamchatka Peninsula. In addition, MISR data were able to capture downwind plume-particle evolution of ash, providing a new means to remotely quantify and monitor the vertical extent and particle characteristics of ash plumes.

## **Landslides**

Documenting the behavior of landslides in response to ongoing climate shifts (e.g. precipitation) and environmental perturbations (e.g. earthquakes) is essential for understanding the mechanisms that control landslide movement. Hu et al., (*Nature Comm.*, 2020) examined the Slumgullion landslide in Colorado from 2011-2018 using four-dimensional surface motions from UAVSAR data to better understand landslide behavior by quantifying landslide rheology, subsurface channel geometry, mass flow rate, and spatiotemporally dependent pore-water pressure feedback. This furthered our

understanding of landslide processes and demonstrates the importance of remotely characterizing inaccessible landslides to reduce the associated hazards.

## Deep-Earth Processes

The dynamics of the mantle and core fundamentally drive the evolution of the Earth's shape, its orientation and rotation, plate motions and deformation, and the generation of the magnetic field. Global-scale research on the Earth's interior utilizes gravity, topography, magnetic, or other geodetic methods and associated modeling and analysis to advance and require the perspectives provided by space-based and other remote-sensing observations. NASA ESI studies also continued to make unique contributions to magnetic field data products representing sources from the core outward. While addressing advances in CORE challenges [5. Deep-Earth, 6. Magnetic field] the studies described below highlight connections to other CORE challenges [1. Plate boundaries, 2. Tectonics and surface processes, 3. Solid Earth and sea level].

### Earth Rotation

Astrometric and geodetic measurements show that the mean position of Earth's spin axis drifted toward Labrador, Canada at an average speed of  $10.5 \pm 0.9$  cm/yr during the 20th century. Understanding this secular polar motion (SPM) is important in global climate modeling, as it provides a link to ice mass balance and sea-level rise. Although glacial isostatic adjustment (GIA) models reasonably explain the direction of SPM, the associated prediction of the amplitude is lacking. Caron and Ivins (*Earth Planet. Sci. Lett.*, 2020) have combined GPS data with geochronological constraints to refine GIA models in Antarctica to better understand and estimate ice mass changes. By correlating GIA to ice mass changes the researchers determined how vertical movements of the solid Earth can masquerade as ice mass changes when observing GRACE data. By correcting for these false interpretations, mass balance measurements from GRACE correlate with those from altimetry data within one sigma. This model can also be used to account for both global and regional 3-D variations in mantle viscosity.

Length of day (LOD) variations occur at a seasonal, long-term, and decadal scale. Seasonal variations are believed to be the result of mass redistribution by the Earth's climate system, long-term variations are the result of geophysical processes, such as GIA, and decadal scale variations are thought to be due to core-mantle coupling. Chen et al., (*J. Geophys. Res.*, 2019) studied these three types of variations and compared them against atmospheric, oceanic, and hydrological (AOH) models from 1962 to 2018. They found LOD variations that oscillate at periods of 2.36, 3.65, and 4.6 years in addition to the previously established 5.9 year oscillation. The three newly identified periods can largely be accounted for by AOH sources, but the 5.9 year oscillation is likely derived from variations in the Earth's interior, likely the core.

## **Magnetic Field**

Polar motion on decadal time scales has long been believed to be influenced by equatorial angular momentum between the solid earth mantle and fluid outer core through the mechanism of electromagnetic (EM) core mantle coupling. Although, past estimates of EM torque coupling are too weak to account for the observed polar motion. Kuang et al., (*Geodesy and Geodynamics*, 2019) examined the EM coupling mechanism and found the toroidal field in the D''-layer at the base of the mantle to potentially be much stronger than that from the advection of the poloidal field in the outer core. The D''- layer toroidal field cannot be observed from geomagnetic observation of the Earth's surface and is missing from previous EM estimates. This could potentially account for the additional torque coupling needed to influence polar motion.

## **Geodetic Imaging**

Synthetic aperture radar (SAR) and interferometric SAR (InSAR) data are critical to enabling many ESI research objectives focused on surface deformation. Significant contributions continued to flow from UAVSAR, and progress continued towards realizing the NASA-ISRO Synthetic Aperture Radar (NISAR) satellite mission. Connected to this is enabling research for SAR, as well as for complementary techniques built on GPS geodetic data.

### **NASA-ISRO Synthetic Aperture Radar (NISAR) Mission**

NISAR (<https://nisar.jpl.nasa.gov/>) has been in Phase C since August 2016, and is approaching Phase D. L-band radar flight electronics at NASA and the S-band radar flight electronics at ISRO are in the integration and test phase. The global pandemic has had an impact on the integration and test phase schedule. In parallel, the flight mechanical systems, including the reflector, deployable book, and launch restraint system, have gone through extensive testing, with integration with the electronics expected later this year, depending on ongoing pandemic impacts.

The solid-Earth team continues to refine their efforts to establish their Algorithm Theoretical Basis Documents and validation processing as an integrated tool using Jupyter notebooks. Annual UNAVCO training on geodetic imaging, given primarily by NISAR project and science team members, has evolved to a virtual fully cloud-based training experience, emulating the way in which NASA anticipates science users interacting with their data – without download, using tools co-located with the data. In 2020, 100 students were accepted to participate from all over the world, using the ASF OpenSARLab platform for processing.

The project held a workshop July 7, 2020 to inform the SNWG of NISAR progress, preceded by a SAR training tutorial in March. Both were virtual. Approximately 70 community members attended each event. The SNWG community has advocated for national land level change products using NISAR and other satellite data. This workshop

informed that community of NISAR plans in this regard and has led to follow-on discussions to foster the integration of NISAR products into end-user systems.

ISRO has developed an airborne radar instrument called “ASAR” that operates at NISAR wavelengths (L-band and S-band). NASA and ISRO agreed to integrate ASAR into the NASA G-III aircraft and conduct science flights throughout the western US. A campaign was conducted in December 2019. NASA selected an ASAR science team, which helped define the campaign. Most of the science focuses on ecosystems and cryosphere applications, as the system is not designed optimally for repeat-pass interferometry. However, the data will be useful across disciplines in understanding the properties of simultaneously acquired L- and S-band images in a variety of natural environments. Processing of the imagery is underway at ISRO, delayed by the pandemic shutdown and slow restart in India, and distribution should begin in Fall 2020.

### **The Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) Facility**

During the time period from June 19, 2019 to June 19, 2020, UAVSAR conducted 56 science/engineering flights totaling 290 flight hours before the pandemic shutdown in mid-March. Between the L- and P-band radars, UAVSAR acquired 479 flight lines over the United States and Canada, participating in 3 major campaigns that included acquiring NISAR terrestrial ecology proxy data in southeast U.S. for calibration/validation, the Arctic Boreal Vulnerability Experiment (ABOVE) campaign in Canada and Alaska, and the SnowEx campaign in the Rockies and the Sierra Nevada. The project supported 19 Principal Investigators and 3 science teams performing research on 5 science disciplines, as well as rapid response efforts and technology development. UAVSAR team also led the accommodation of Indian Space Research Organization’s (ISRO) airborne L/S-band SAR (ASAR) aboard NASA’s Gulfstream jet to conduct science campaigns in the US to prepare the science community for the NISAR mission. The first ASAR campaign in December 2020 was conducted over western US and Alaska and included 9 science/engineering flights totaling 47 flight hours. ASAR acquired 92 flight lines for 14 Principal Investigators performing research on 10 science disciplines as well as calibration efforts.

Since June 2019, science results based on UAVSAR data were published in 52 refereed journal papers, 52 refereed conference papers, and 2 PhD theses, covering topics in applied sciences, cryosphere, hydrology, land cover/land use change, remote sensing theory, solid earth, terrestrial ecology, disaster response, and SAR processing techniques. We highlight two of these publications:

The Glacier and Ice Surface Topography Interferometer (GLISTIN-A) is a JPL developed high-resolution single-pass InSAR instrument designed to be flown on UAVSAR. Lundgren et al., (*Geophys. Res. Lett.*, 2019) flew GLISTIN-A over the Kilauea lava flow field during it’s 2018 eruption on 7 days between 18 May and 15 September to better characterize topographic changes related to eruption in order to estimate the lava volume change. They found that both the lower east rift zone (LERZ) and caldera lava volume change were approximately linear.

Complementary to their *Nature*, 2020 publication, Hu and Bürgmann (*Geophys. Res. Lett.*, 2020) used UAVSAR acquired InSAR data and LiDAR DEM landslide frontal toe thickness to determine the dynamics of the Slumgullion landslide. They jointly analyzed these data for intrinsic velocity by augmenting the Bingham plastic model. The resulting detailed displacement maps provide insight into local variations in flow magnitude and orientation. This method highlights the capability of airborne and spaceborne remote sensing data to understand the rheology of debris slides.

### **Geodetic Imaging Enabling Research**

InSAR and GPS data availability and processing methods are critical to many avenues of ESI science, while also providing high-resolution maps and time series of surface deformation applicable to many scientific and applied studies. Atmospheric and vegetation derived noise is a particularly prevalent and challenging component of space-based InSAR observations that must be accounted for to accurately derive underlying surface displacements in the data. Bürgi and Lohman (*IEEE Transactions on Geoscience and Remote Sensing*, 2020) identified the impact of forest disturbance on InSAR time series in the Pacific Northwest between 2000 and 2018. In this study ALOS-1 InSAR data were compared against Landsat and Sentinel-2 data to identify areas with vegetation change. They identify how changes in vegetation can impact InSAR results and demonstrate the need to independently identify areas with vegetation change to reduce the risk of misidentifying it as surface deformation. Murray et al., (*Remote Sens. Environ.*, 2019) focus on providing suggestions for the mitigating tropospheric noise for the InSAR community by statistically comparing the many different tropospheric correction models available. Spatial structure functions were found to be the most useful metric for comparing performance and the Generic Atmospheric Correction Online Service for InSAR (GACOS) was found to outperform other correction models on average.

## **Space Geodesy Program**

NASA's Space Geodesy Program (SGP) (<http://space-geodesy.nasa.gov/>) supports the production of foundational geodetic data that enable positioning, navigation, and timing applications and many of the scientific discoveries and accomplishments highlighted in the other sections of this report. During the past year, SGP continued the development and deployment of a modern network that includes co-located next-generation Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite System (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) stations.

### **Space Geodesy Network Deployment**

SGP continued to advance the VLBI Global Observing System (VGOS) by operating its broadband VLBI stations at Kōke'e Park Geophysical Observatory (KPGO) in Hawaii, Goddard Geophysical and Astronomical Observatory (GGAO) in Maryland, and Westford in Massachusetts. Baver and Gipson, (*Journal of Geodesy*, 2020) examined the

source strength and sky coverage of the two INT01 VLBI stations. These stations observed a small set of strong quasar sources, but in the past these sources were unevenly distributed, resulting in high UT1 formal errors. This was improved in 2009 by implementing the maximal source strategy (MSS), which cut the amount of error observed in half. However the introduction of weaker sources once again increased these errors. Baver and Gipson introduce a new “Balanced 50” (BA50) strategy which balances both source strength and sky coverage when identifying sources, this strategy is now being used in INT01 scheduling on a trial basis.

### **Terrestrial Reference Frame Combination**

The Terrestrial Reference Frame is the foundation for positioning and timing for navigation and proper interpretation of scientific measurements. The standard for the most demanding scientific applications is the International Terrestrial Reference Frame (ITRF). Preparations for NASA/JPL support of the next ITRF solution, planned for 2020, are nearing completion. As part of the International Earth Rotation and Reference System Service (IERS) effort to determine an update to the ITRF, “ITRF2020”, NASA/JPL is planning on producing three solutions for evaluation by the IERS:

1. A standard solution to be considered as a candidate to be selected as the ITRF2020 solution. In this, NASA/JPL will utilize modernized software to find the optimal combination of Network solutions for each of the major Space Geodesy Techniques (DORIS, GNSS, SLR, and VLBI) and results from local surveys from co-located sites;
2. A TRF solution, based on a combination of network solutions, that also results in a determination of Earth Orientation Parameters and the Celestial Reference Frame;
3. A TRF solution that is based on the combination of observations from the major space geodesy techniques. This solution could lead to a potentially groundbreaking methodology for improving the TRF and, more generally, to significant improvements in positioning and timing of scientific measurements.

All of the NASA/JPL TRF solutions have the benefit of being easily updated using new measurements, prolonging the time between data reprocessing and selection of new ITRF solutions.

Work on the TRF solution combined at the observation level has begun and procurement of the computer discs required for data processing has been completed. The bulk of the work on this TRF solution will take place over the next year and a half. Several publications in the past year have focused on expanding the instrumentation used in identifying the TRF and improving the data collected.

Razeghi et al., (*J. Geophys. Res.*,2019) incorporated GRACE Geopotential data into TRF research by developing a method that co-estimates the geocenter of motion and the gravitational potential field by simultaneously inverting a set of globally-distributed GPS displacement time series and temporally-varying GRACE gravity data. These estimates

were consistent with SLR results within 1 mm when compared to the monthly variability average from 2003-2016.

Starting in 2015 the reliability of the SLR network was improved by transitioning from the metric of Time Interval Units (TIU) for ranged measurements with picosecond-precise Event Timer Modules (ETM). Varghese et al, (*Journal of Geodesy*, 2019) verified and validated the effectiveness and this new metric using a mutli-ETM comparison at two SLR stations and found that this transition will enable the next generation SLR network to improve it's maximum operating rate from 10 Hz to 2 kHz.

### **Global GNSS Network**

The NASA Global GNSS Network (GGN) remains a state-of-the-art scientific GNSS network, providing high quality, multi-GNSS measurements to NASA and researchers throughout the world through participation with the International GNSS Service (IGS). The NASA/NOAA-NGS Agreement, put in place this last year, was the result of a long period of significant interagency communications and negotiations to ensure a mutually beneficial outcome. The agreement integrates the NASA Global GNSS Network with other US stations into the National Geodetic Survey (NGS) Foundation Continuously Operating Reference Stations (CORS) Network. The result will be “to ensure a sufficient density of operating Foundation CORS throughout the US and its territories, improving local ties and thereby each station’s contribution to the ITRF and the National Spatial Reference System (NSRS).”

Several algorithms leveraging high-rate real-time GNSS (HR-GNSS) have been proposed in an effort to supplement earthquake monitoring. Melgar et al., (*J. Geophys. Res.*, 2020) studied 1 year of GNSS data over 213 sites spanning from Southern California to Alaska to better characterize the behavior of noise for these data and to propose the most effective methods of processing HR-GNSS data using several reference noise models. They concluded that while important improvements still need to be made to reduce the number of outliers in time series, the present quality of the data is more than sufficient for monitoring large earthquakes.

### **JPL Geodetic Analysis Center**

The JPL Geodetic Analysis Center has made progress on all fronts while still successfully producing and delivering a full suite of GPS analysis products and sustaining GipsyX Geodetic Data Analysis software for NASA and other researchers. Sustainment activities include developing GipsyX software to adapt to Block III GPS and new data formats from ground networks.

A major effort has been devoted to reprocessing GPS data for contributions to the development of the next ITRF, ITRF2020. This reprocessing requires analysis of GPS measurements going back to the early 1990s. Reprocessing the first set of GPS orbits (2009-2018) is complete and has been provided to the International GNSS Service.

A major milestone in the transition from GPS-only to multi-GNSS operations was also completed. Six months of 3-constellation (GPS+Galileo+GLONASS) orbit and clock products were generated and delivered to users for test and validation. Prior to delivery these products were tested and shown to be at least as good as current GPS-only Quick-Look(QL)/Rapid products, and Galileo orbits were shown to be competitive with other IGS analysis centers. This work also resolved many issues associated with producing such multi-constellation products using GipsyX software.

Development of multi-technique capabilities also saw a major accomplishment. VLBI analysis capabilities to estimate VLBI station positions were demonstrated and validated. Work on determining Earth Orientation Parameters has started and is hoped to be complete by the end of the year, in time to support a major research effort in advanced methods for establishing terrestrial reference frame solutions, co-sponsored by NASA and the National Geospatial-Intelligence Agency (NGA).

Finally, 170 new GNSS ground stations were added to standard processing producing high precision ground station position time series. Access to these ground station position time series by researchers will support many scientific applications, including groundwater monitoring in the US to better understand the impacts of drought and flooding. The plan is to add 100 – 200 stations per year based on the quality of the stations and their scientific importance.

### **SGP International and Interagency Cooperation**

SGP continues to be a key participant in the United Nations Global Geospatial Information Management's Subcommittee on Geodesy. A key highlight here is the move to establish a UN GGIM Global Geodetic Centre of Excellence. If successfully implemented, the Centre of Excellence could provide UN-funded staff for advocacy and assistance to nations to invest in geodetic infrastructure and education. Through SGP's representation on all of the Subcommittee's Working Groups (Governance; Geodetic Infrastructure; Policies, Standards and Conventions; Education, Training and Capacity Building; and Communication and Outreach), SGP is ensuring that the Centre is complementary to and not competing with the International Association of Geodesy and NASA objectives.

### **Science Community Engagement**

The National Academy of Sciences (NAS) completed a new study leading to publication of the report [\*Evolving the Geodetic Infrastructure to Meet New Scientific Needs\*](#) (NAP, 2020). The study was jointly funded by NAS and NASA (ESI, Physical Oceanography, Cryospheric Sciences, and Research & Analysis) with ESI as the NASA Headquarters point of contact. The report reaffirms broad Earth science needs for space geodesy network products.

## **SGP Contributions to Broad Science Mission Directorate Objectives**

### ***Testing the Theory of Relativity***

The weak equivalence principle is at the foundation of General Relativity and of most gravitational theories. Ciufolini et al., (*Scientific Reports*, 2019) used SLR from three laser-ranged satellites to confirm to approximately one part per billion of the fundamental weak equivalence principle in the Earth's gravitational field. This was a previously untested range made with the previously untested laser-ranged satellite materials of LARES, LAGEOS, and LAGEOS 2.

### ***Surface Mass Change***

Surface mass change provides an integrated global view of the evolution of Earth's water cycle and energy balance and acts as a fundamental climate system indicator. GRACE monitored mass change every month from 2002 through 2007. In June 2018 the monitoring was replaced by GRACE-FO. Landerer (*Geophys. Res. Lett.*, 2020) demonstrated the improved performance of GRACE-FO by comparing its observation of interannual terrestrial water variations associated with excessive rainfall in the Central US and Middle East, drought in Europe and Asia, and ice melt in Greenland and found them to be consistent with independent mass change estimates. This study provides a high confidence that no intermission bias exists from GRACE to GRACE-FO measurements. To further improve these data, Wu et al., (*J. Geophys. Res.*, 2020) incorporated GNSS and GRACE data using a Kalman filter and applied this combination to estimated surface mass variations and geocenter motion. This combination reduced the surface mass change discrepancies in GNSS data and provided more robust geocenter motion results.

It's well documented that SLR has an increased ability to measure Earth's dynamic oblateness ( $C_{20}$ ) compared to GRACE/GRACE-FO, it is common practice to replace GRACE  $C_{20}$  values with those of SLR. Loomis et al. (*Geophys. Res. Lett.*, 2020) demonstrates that the  $C_{30}$  gravity coefficient is also poorly observed by GRACE/GRACE-FO and that it has a large impact on recovered Antarctic Ice Sheet mass changes. They suggest replacing GRACE/GRACE-FO  $C_{30}$  measurements with those from SLR when making Antarctic Ice Sheet mass change estimates.

### **Section 1.1.8.5 Water and Energy Cycle Focus Area**

Research funded by NASA's Water and Energy cycle focus area (WEC) seeks to improve our fundamental understanding of the water and energy cycles by developing tools and techniques that expand our abilities to: 1) detect, measure, track, model, and forecast global water storage and dynamics, 2) quantify how energy is transferred from the tropics to higher latitudes, and 3) expand our ability to assess water quality. The WEC community uses satellite and airborne remote sensing observations in conjunction with *in situ* field measurements to advance our scientific understanding of the natural and anthropogenic processes influencing water distribution and to predict how changing climatic factors may influence water availability thereby improving society's ability to manage water resources. These objectives are accomplished through two separate programs within the Water and Energy Cycle Focus Area: NASA Energy and Water Cycle Study Program) and the Terrestrial Hydrology Program (THP). NEWS aims to resolve all fluxes of water and the corresponding energy fluxes involved with water changing phase. The THP studies the hydrologic processes associated with runoff production, fluxes at the land-air interface, terrestrial water stores (i.e. surface water, seasonal snowpack, soil moisture, and groundwater), and extreme hydrological events. THP also fosters the development of hydrologic remote sensing theory, the scientific basis for new hydrologic satellite missions, hydrologic remote sensing field experiments, and identifies new capabilities that have the potential to support decision makers.

The WEC research portfolio is an ongoing balance of supporting research that can be advanced with the current constellation of airborne and satellite sensors, preparing for new missions that are under construction (i.e. SWOT and NISAR), and identifying new and innovative techniques/technology that will allow us to ask the next generation of scientific questions that were not possible a few years ago, all within a limited budget profile. Below are highlights of WEC Focus Area funded research accomplishments that have matured in FY2020 and represent the research that has been funded over the past several ROSES cycles.

The scope of NASA's Water and Energy Cycle (WEC) focus area includes both the 1.1.8 "characterizing the behavior of the Earth system" performance goal, and the 1.1.9 "improve predictive capability" performance goal. WEC activities supporting performance goal 1.1.8 include observation, analysis, and interpretation of water and energy cycle fluxes and states using satellite, airborne, and in-situ instruments, along with computational and other assessment tools. Publications under this category contribute to understanding and improving the capabilities of observations, such as retrievals of states and fluxes, characterizing and quantifying error sources and uncertainties, as well as characterizing and measuring the quality of surface. Section 1.1.8 begins with three cross-cutting publication that highlight climatic influences to water storage followed by subsections that showcase WEC's research in snow, surface water, high mountain Asia, soil moisture, groundwater, and ecosystems/drought.

#### **Water Budget and Water Cycle Dynamics**

The bulk of WEC research activities focus on the characterization, quantification, and modeling of the different elements of the terrestrial water cycle: precipitation, snow, surface water, soil moisture, biological/ecosystem water, and groundwater. These activities include advancing science from our current missions (i.e. SMAP, GPM, MODIS, GRACE-FO) and new research supporting missions that are in development (i.e. SWOT and NISAR). Several WEC funded activities came to fruition with an updated accounting of the global water and energy budgets, leveraging many NASA investments to develop and produce individual variable data sets, from observations and reanalysis. Investments in these types of activities will enhance overall assessment through improved accounting of individual water budget/cycle terms. NASA is dedicated to global observations from spaceborne platforms. These investments align to support different stages of satellite mission development, data use, and societal benefit. This section begins with three cross-cutting publications that highlight climatic influences to water storage followed by subsections: Snow, Surface Water, High Mountain Asia, Soil Moisture, and Groundwater.

Mountains are the water towers of the world, meeting a substantial part of both natural and anthropogenic water demands. These mountain environments are highly sensitive to climate change, yet their importance and vulnerability had not previously been quantified at the global scale. Immerzeel *et al.*, 2020 ([Nature](#)) present a global water tower index (WTI), which ranks all water towers in terms of their water-supplying role and the downstream dependence of ecosystems and society and conclude that the most important (highest WTI) water towers are also among the most vulnerable, and that climatic and socio-economic changes will affect them profoundly.

The movement of water among the different hydrology reservoirs are a result of processes that are at the core of important physical Earth-system feedbacks, which fundamentally control the response of Earth's climate to the greenhouse gas forcing it is now experiencing, and are therefore vital to understanding the future evolution of Earth's climate. Stephens *et al.*, 2019 ([Proc. of Royal Society](#)) provide a review of progress toward quantification of the water stored in Earth's main water reservoirs (ocean, cryosphere, atmosphere, surface water and sub-surface water), and exchanges of water between the reservoirs, with emphasis placed on the progress achieved by using the latest advances in Earth Observation from space. In addition to providing an updated quantification of these stores and fluxes, the authors emphasize that (1) the processes controlling these fluxes are among the most critical Earth-system feedbacks which control the response of Earth's climate to the greenhouse gas forcing it is now experiencing, (2) advancing the development of approaches for assimilating data from relevant sources is a high priority for improved understanding of the stores and fluxes, (3) maintaining sources of *in situ* data is another high priority, and (4) Earth's hydrological cycle, including human influences on it, is shown to significantly affect the apparent rate of global mean sea level rise by substantial amounts for extended periods of time.

The climate of the conterminous United States has been changing over the past several decades with trends indicating that the current summers are longer and warmer compared to anytime in the past U.S. record and that this trend has been accelerating over the past

several decades. Most of the research related to understanding the impact of these climatic influences on hydrology trends has focused on local analysis. Jasinski *et al.*, 2019 ([J. of Hydrometeorology](#)) estimate terrestrial hydrologic trends over the conterminous United States are for 1980–2015 using the National Climate Assessment Land Data Assimilation System (NCA-LDAS) reanalysis. Overall, NCA-LDAS demonstrates capability for quantifying physically consistent, U.S. hydrologic climate trends over the satellite era. The implication for the current analyses is that the U.S. West and Southwest are trending to increasingly drier conditions under a climatically moisture-limited system, while the U.S. East and North behave as energy-limited systems, trending toward more temperate conditions.

### ***Snow***

Snow remains one of the significant challenges to remote sensing of the water cycle. Unlike with other variables, a single remote sensing technique and/or wavelength of observation have proven insufficient to resolve Snow Water Equivalent (SWE) and other snow properties, especially at the high spatial scales (~100s of meter) that are necessary to investigate snowpack dynamics. Therefore, WEC continues to invest in a variety of research and technical approaches to better characterize snow. The Focus Area supported SnowEX, a large airborne and in situ data collection campaign that evaluated several different types of snow remote sensing techniques collected at the same time and location. This GPRA cycle produced a number of publications advancing our understanding and capabilities in snow science including a 35 manuscript Water Resources Research Special Edition titled: *Advances in Remote Sensing Measurement, and Simulation of Seasonal Snow*. Below are three publication groupings that highlight larger scale snow analysis, new techniques for measuring SWE, and results for the SnowEx airborne campaigns.

Climate warming has altered patterns of snow accumulation and melt throughout the seasonal snow zone in the western United States. Understanding these patterns and potential measurement biases will advance our overall ability to better model their behaviors. Jennings and Molotch, 2020 ([Cryospheric Sciences](#)) explore how specific climate change impacts drive changes to snowpack and melting. From simulations of snow accumulation and melt at a U.S. Long Term Ecological Research site, they found that snowpacks in alpine regions were less sensitive to climate warming than in subalpine regions. The results suggest that locations with relatively lower cold content, like the subalpine site studied, are likely to be more sensitive to producing increased winter melt as warming continues over the coming decades. Wrzesien *et al.*, 2019 ([Water Resources Research](#)) compare four commonly used global data sets to understand whether they provide consistent mountain Snow Water Storage (SWS) estimates. The models agree to within  $\pm 36\%$  for global SWS and within  $\pm 21\%$  for SWS in mountain areas, however significantly higher differences of SWS estimates between each model and a high-resolution model for North American mountain SWS. The authors conclude that more research must be done to characterize water resources in snow-dominated regions, particularly in mountains.

A large amount of freshwater resources are stored in the snowpack, a primary source of water for streamflow in many places at middle-to-high latitudes, therefore, the WEC Focus Area continues to invest in new approaches that advance our ability to uniquely measure and track spatially varied SWE as a key parameter in the water cycle.

Oveisgharan *et al.*, 2020 ([Remote Sensing](#)) evaluate the conditions for which two recent algorithms (dual frequency [X- and Ku-band], dual polarization backscattered power and differential interferometry) are valid for retrieving SWE and identify the regions and the amount of snow in the US that satisfy these conditions. Understanding the limitations of these important SWE measurement methods is a critical precursor for improved SWE estimates. Snow albedo is a dominant control on snowmelt in many parts of the world. Bair *et al.*, 2020 ([The Cryosphere](#)) present two new contributions to improved use of snow albedo measurements for improving estimates of SWE: (1) an updated albedo model where grain size and light absorbing particle content are solved for simultaneously and (2) multiyear comparisons of remotely sensed and in situ albedo measurements from three high-altitude sites in the western United States. The authors conclude that use of remotely sensed albedo, when available, is superior to conventional snow age-based approaches for SWE retrievals in all aspects except simplicity.

[SnowEx](#) is a five-year program initiated and funded by WEC-THP to address the most important gaps in snow remote sensing knowledge and lay the groundwork for a future snow satellite mission. It focuses on airborne campaigns and field work, and on comparing the various sensing technologies, from the mature to the more experimental, in globally-representative types of snow. Research from the SnowEx campaigns are producing a number of publications with two highlighted here. Webb *et al.*, 2020 ([Water Resources Research](#)) determine the impact of forest boundary effects on SWE accumulation distribution patterns within forest stands using a unique ground penetrating radar dataset collected during SnowEx in Grand Mesa, Colorado. The authors found that the largest within-stand boundary effect occurred on the leeward side of stands with a mean extent of 4.3 times the mean canopy heights. In contrast, windward within-stand boundary effects showed a mean extent of 3.7 times the mean canopy heights. This research provides motivation and insight for future investigations to improve understanding of this complex process, which has potential for improving snowpack modeling. Currier *et al.*, 2020 ([Water Resources Research](#)) compared snow depth measurements made using three different techniques during NASA's 2017 SnowEx field campaign at Grand Mesa, CO: Airborne Laser Scans (ALS), Terrestrial Laser Scans (TLS), and snow-probe transects. Based on comparisons with TLS and snow depth probes, the authors found that ALS captured snow depth magnitude with better than or equal agreement to what has been reported in previous studies and showed the ability to capture high-resolution spatial variability. Improved snow depth measurements hold potential for improving SWE estimates.

### ***Surface water***

The focus area has made investments to improve our ability to resolve surface water and measure river discharge, including preparing for the upcoming SWOT Mission. Both are important topics to pursue and to stay current with the advances in land modeling efforts that have moved from a traditional climate paradigm, which disregards horizontal

movement of water, to one that models surface processes more comprehensively and at higher spatial resolutions. This advancement can facilitate the use of WEC observations to support carbon cycle research that focuses on resolving roles of surface water and rivers in the carbon budget. Furthermore, as we prepare for the SWOT and NISAR missions, and time-series data from GRACE-FO missions mature, technology and algorithm development are beginning to support new scientific advancements with increasing contributions in future GPRA cycles. There were 54 publications in the past GPRA cycle that spanned a variety of surface water related science and technique development ranging from more comprehensive regional studies (i.e. Yukon and Mekong Rivers) to exploring new capabilities with ICESat-2. In this section, we will feature a pair of publications that seek to better characterize surface water dynamics through different approaches: fusion of SAR and optical imagery and the use of GNSS reflectometry, and AirSWOT measurements. We also highlight a trio of SWOT related publications.

Consistent estimation of water surface area from remote sensing remains challenging in regions with diverse conditions such as vegetation, mountainous topography, and persistent cloud cover. High-resolution optical imagery, which is often used for global inundation mapping, is highly impacted by clouds, while Synthetic Aperture Radar (SAR) imagery is not impacted by clouds, but is affected by both topographic layover and vegetation. Ahmad *et al.*, 2020 ([IEEE Transactions on Geoscience and Remote Sensing](#)) developed and evaluated surface water maps created by fusion of optical and SAR data. Results for three study sites indicate that the fusion approach can improve the overall accuracy of the maps by up to 3.8%, 18.2%, and 8.3% compared with using the individual products of Landsat8, Sentinel-1, and Sentinel-2, respectively, while providing increased observational frequency. The authors concluded that the SAR-visible fusion technique has high potential for improving satellite-based surface water monitoring and storage changes, especially for smaller water bodies in the humid tropical climate of South Asia.

Mapping wetland extent and quantifying how the extent changes over time is an important task for both scientific and societal applications, but current techniques used to map wetlands are not able to fully capture the sometimes-rapid changes in wetland extent, high spatial variability in inundated or saturated areas, or successfully map water beneath dense vegetation canopies. Lowe *et al.*, 2020 ([Remote Sensing](#)) present an innovative use of GPS signals to map inundated areas of wetlands. The authors found that the aircraft-based measurements have characteristics superior to that obtained from ESA Sentinel-1 SAR data, and currently available space-based Global Navigation Satellite System-Reflectometry (GNSS-R) data. Their results indicate that, at aircraft altitudes, forward-scattered GNSS signals can be used to map inundated regions at high resolutions, even in the presence of dense overlying vegetation, whether that vegetation consists of short plants or tall trees.

The upcoming SWOT mission is expected to significantly increase our understanding of river flowrates in ungauged basins, and water storage in surface water reservoirs. A considerable amount of SWOT-related research has been funded in recent years in

preparation for this mission. The follow publications are a subset of the overall effort and focus on SWOT's measurement characteristics, temporal sampling for discharge, and the assimilation of SWOT data into hydrological models.

Water surface elevations (WSE) derived from SWOT's interferometric synthetic aperture radar (InSAR) data are potentially vulnerable to contamination from layover, a phenomenon wherein radar returns from multiple locations arrive at the sensor simultaneously, rendering them indistinguishable. Durand *et al.*, 2020 ([Remote Sensing of Environment](#)) present their research on how the radar artifact of layover impacts the accuracy of river flow rate estimates. At a global scale, their calibrated model shows that layover causes expected height uncertainty to increase by only a modest amount (from 9.4 to 10.4 cm at the 68th percentile). The 68th percentile of the slope uncertainty increases more significantly, from 10 to 17 mm/km. Nonetheless, the authors find that the impact of layover on SWOT river discharge is expected to be small in most environments.

SWOT will measure almost everywhere on Earth between two and ten times every 21 days, with more observations at higher latitudes. This temporally and spatially varied collection pattern may produce sampling biases when fully assessing river discharge frequency behavior. Nickles *et al.*, 2019 ([Geophysical Research Letters](#)) evaluate how the particular sampling strategy of the NASA SWOT mission may impact understanding of surface water characteristics. The researchers found that for their study area, the Mississippi River Basin, in general, SWOT temporal sampling has minimal impact on derived discharge quantiles, but the combination of both temporal sampling and uncertainty leads to underestimated discharge. At the highest levels of discharge, the negative bias used for SWOT discharge uncertainty is expected to mitigate this negative bias in measured discharge.

The highly intermittent and sparse nature of the SWOT river observations in both space and time poses a major challenge to users for most applications, especially with integration into computer models. Yang *et al.*, 2019 ([Remote Sensing of Environment](#)) designed an observing system simulation experiments (OSSE), in which using synthetic SWOT observations were combined with in situ stream gauges to provide insights on potential improvements to the assimilation of SWOT data into their Inverse Streamflow Routing model. The authors tested the impact of introducing spatiotemporal error correlations to improve the gap-filling capability in SWOT discharge assimilation. While all 16 basins studied benefitted from this method, a subset of basins that had poorly constrained initial conditions and fewer SWOT observations, showed much larger performance gains using their approach.

### ***High Mountain Asia***

The Himalayan mountain glaciers encompass the largest reservoirs of freshwater on Earth outside of the polar regions. The melting of snow and glaciers in High Mountain Asia (HMA) contributes up to 70% of the annual water supply of over 1.4 billion people in the region. In 2015, NASA formed the High Mountain Asia Science Team (HiMAT) as an interdisciplinary science team that focused on studying glaciers, snow, permafrost,

and precipitation to improve our understanding of regional changes, water resources, and induced impacts, while furthering NASA's strategic goals in Earth system science and societal applications. High Mountain Asia continued to be an important research theme in FY2020. There were 24 HMA related publication during this GPRA cycle, three of which are highlighted here. There will also be a special issue of the journal *Frontiers in Earth Science* that will combine a number of recently submitted publications on High Mountain Asia hydrology into a single issue. The second HiMAT was selected and began new research in the spring of 2020.

Changes in terrestrial water storage (TWS) in High Mountain Asia (HMA) could have major societal impacts, as the region's large reservoirs of glaciers, snow, and groundwater provide a freshwater source to more than one billion people. Loomis *et al.* 2019 ([Frontiers in Earth Science](#)) sought to quantify and close the budget of secular changes in TWS through an assessment of the HMA terrestrial water storage trend using GRACE data, Digital Elevation Models (DEMs), well observations, and a suite of land surface model simulations from the NASA Land Information System (LIS). Their work shows support for a new high-resolution regression trend product for the HMA region, which reports a trend of  $-37.8 \pm 10.4 \text{ Gt yr}^{-1}$ . The accurate characterization of total TWS trends and its components presented by the authors is critical to understanding the complex dynamics of the region, and is a necessary step toward projecting future water mass changes in HMA.

Snow and ice play critical roles worldwide in water resources and climate where seasonal and perennial snowpacks and glaciers act as natural reservoirs, providing runoff during the hottest months of the year, and in complementary timeframes. In addition to direct runoff resources, snow and ice play a critical role in climate: significant portions of incident solar radiation are reflected away from the earth surface due to the high albedo of snow and ice, resulting in a cooling effect critical to the surface energy budget. Lund *et al.*, (2020: [Frontiers of Earth Science](#)) focused on use of Sentinel-1 synthetic aperture radar data to monitor the development of wet snow during snowmelt in the upper Indus basin in Pakistan from 2015 to 2018. Comparison with snow maps derived from ESA Sentinel-2 data, shows good pixel-wise agreement of 84–89% at different times in the melt season. This agreement encourages the use of SAR-derived snow conditions maps in areas with significant cloud cover, for example in monsoonal regions of HMA. The authors expect that data derived using these methods will be valuable for improving energy balance and runoff models. They also found that SAR indications of snowpack conditions can offer critical insight into energy balance processes on a subseasonal timescale, in an area with limited field measurement and variable cryospheric responses to climate.

Despite the importance of HMA as a critically important area of freshwater storage and water availability, significant uncertainty in the characterization of terrestrial water budget components exists due to the lack of reliable and spatially-distributed ground measurements as well as limitations in the modeling and remote sensing estimates. Yoon *et al.*, 2019 ([Frontiers in Earth Science](#)) examined the errors and uncertainties in the key terrestrial water budget variables of precipitation, evapotranspiration, runoff, terrestrial

water storage, and snow cover over HMA using a suite of uncoupled land surface model (LSM) simulations forced with prescribed meteorology. They found precipitation datasets that incorporate information from gauges are found to have higher accuracy with low Root Mean Square Errors and high correlation coefficient values. A comparison of ET, snow cover fraction, and changes in TWS estimates against remote sensing-based references confirms the significant role of the input meteorology in influencing the water budget characterization over HMA and points to the need for improving meteorological inputs.

### ***Soil Moisture***

Soil moisture is the vital connector between surface water and groundwater, and it influences precipitation runoff, snowmelt volumes, and many fluvial hazards. Soil moisture is also the interface between water and plants for many ecosystems making it an important connection between the water, energy, and carbon cycles. The launch of SMAP in 2015 has made it possible to begin to address global soil moisture issues. Similarly, as algorithms improve for analyzing GRACE data, it is becoming possible to better characterize soil moisture contributions to GRACE time-series data. This section highlights a small subset of the overall 42 soil moisture manuscripts that were published during this GPRA cycle. The highlighted publications below focus on continued technology and algorithm development for soil moisture retrieval, ROSES funded research, and the development of new NASA soil moisture products.

P-band SAR is an effective tool for soil moisture retrieval. Chen *et al.*, 2019 ([IEEE Transactions on Geoscience and Remote Sensing](#)) used P-Band radar data and a 3-layer model to retrieve the dielectric constants (representing unfrozen water content) and active layer thickness (ALT, representing water table and thaw depths) of the surface and saturated layers of permafrost on the Alaska North Slope. The authors show that the retrieved ALT errors are generally low for sites where the *in situ* measurements of ALT are smaller than 0.55 m, however ALT is generally underestimated for the sites where the *in situ* ALT is larger than the P-band sensing depth. The retrieval results also show that the active layer properties are strongly influenced by the land cover types at the regional scale, and not as much by the North-South temperature gradient. Improved understanding of permafrost active layer dynamics are needed to improve understanding of the interplay between permafrost and changing climate and land surface conditions. Yueh *et al.*, 2020 ([IEEE Geoscience and Remote Sensing Letters](#)) demonstrated high accuracy retrieval of surface soil moisture using reflected P-Band microwave transmissions from U.S. Navy communication satellites. The experimental data and soil moisture retrieval analyses lend support to the use of P-band signals of opportunity for remote sensing of soil moisture. The data also indicate the limitation of single frequency observations, suggesting the requirement of multiple frequencies to enable root zone soil moisture remote sensing because the surface soil moisture plays a critical role in the change of reflectivity even at P-band frequencies.

The further development and refinement of algorithms contribute to our characterization and understanding of global soil moisture dynamics. The following trio of publications advance soil moisture retrieval with GRACE, SMAP, and L-band SAR. First, Sadeghi *et*

*al.*, 2020 ([Journal of Hydrology](#)) present a new approach to retrieving Surface Soil Moisture (SMS) data from the NASA GRACE mission. The GRACE-based SSM is found to be in a reasonable agreement with in-situ data and highly correlated with retrievals from the NASA SMAP and ESA SMOS missions, especially over wet regions where the assumption that net water flux is well approximated by the change in terrestrial water storage with time holds valid. This approach is particularly useful for areas, such as heavily vegetated regions, which are difficult to monitor using conventional microwave data sources. Second, Chaubell *et al.*, 2019 ([IEEE Transactions on Geoscience and Remote Sensing](#)) demonstrated a modification of the SMAP Dual Channel Algorithm (DCA) for improved soil moisture retrieval. The retrieval performance of the modified DCA is assessed and compared with the SMAP Single Channel Algorithm (SCA-V) and the unmodified DCA using four years of in situ data from core validation sites and sparse networks. The assessment shows that SCA-V still outperforms all the implemented algorithms, however the modified algorithm also enables the retrieval of vegetation optical depth, which has important uses in other research, such as transpiration rate retrievals. Finally, Gao *et al.*, 2020 ([Remote Sensing of Environment](#)) describe a new algorithm called Combined Constrained Multi-Channel Algorithm (C-CMCA) for simultaneous retrieval of soil moisture (SM) and vegetation optical depth (VOD) in L-band with improved resolution. Unlike widely used algorithms, the new approach optimally fuses multiple sources of surface temperature DATA and confines the retrievals to their feasible climatological range. The authors show that the algorithm can decrease the root mean squared error (RMSE) of SM by 78% and VOD by 81% when compared with the unconstrained version, and can decrease the RMSE error of SM by 54% and VOD by 7% when a single source of surface temperature is used.

In-depth knowledge about the global patterns and dynamics of land surface net water flux (NWF) is essential for quantification of depletion and recharge of groundwater resources. Net water flux cannot be directly measured, and its estimate as a residual of individual surface flux components often suffer from mass conservation errors due to accumulated systematic biases of individual fluxes. Sadeghi *et al.*, 2020 ([Journal of Hydrometeorology](#)) demonstrated for the first-time direct estimation of global land surface Net Water Flux (NWF), an essential measurement for quantification of groundwater depletion and recharge, based on soil moisture retrievals from the ESA SMOS and NASA SMAP missions. In conjunction with precipitation and evapotranspiration retrievals, the NWF estimates additionally provide a new means for retrieving global infiltration and runoff from satellite observations. However, the efficacy of the proposed approach over densely vegetated regions is questionable, due to the uncertainty of the satellite soil moisture retrievals and poor representation of transpiration by deeply rooted plants in the proposed model. The authors find that future research is needed to advance this modeling approach to explicitly account for plant transpiration.

Socially and economically costly extreme weather events have become more prevalent in the last decade. Forgotson *et al.*, 2020 ([IEEE Journal of Selected Topics...](#)) use case studies to show the importance of improved soil moisture estimates for improved warnings for extreme climate and weather related phenomenon to help mitigate the impacts of these extreme events. Applications of SMAP soil moisture information are

already helping to better predict and monitor weather and climate phenomena such as floods and droughts, as well as food security and agricultural productivity. Surface soil moisture state information from SMAP helps to determine the capacity of soil to absorb further infiltration due to precipitation and/or snowmelt, thus providing useful guidance on the potential for flooding. Additionally, use of SMAP data can improve knowledge of the land surface initial conditions which is critical for accurate weather forecasts. As climate change is expected to continue, effective monitoring and early warning systems such as described above become increasingly important to help mitigate the possible adverse impacts of climate change.

More than half of the global land area undergoes seasonal frozen and thawed conditions that constrain eco-hydrological processes. The freeze-thaw (FT) retrieval from satellite microwave remote sensing detects landscape changes between frozen and non-frozen conditions due to the strong dependence of surface microwave emissions on liquid water abundance. Youngwook et al., 2019 ([Remote Sensing](#)) evaluated the latest FT algorithms for SMAP using daily in situ surface air temperature measurements from approximately 5000 weather stations located across the globe. The authors found that the PM overpass FT results exceed the targeted 80% accuracy threshold for the SMAP baseline mission requirement. They found that AM FT accuracy is significantly lower than PM FT accuracy, but generally exceeds the 70% accuracy threshold of the minimum mission requirement. Spatial patterns and the timing of landscape FT state transitions have a major influence on eco-hydrological processes in areas where frozen temperatures are a significant part of the annual cycle.

Colliander *et al.*, 2019 ([Water Resources Research](#)) showed that U.S. Department of Agriculture National Agricultural Statistics Survey (NASS) visual assessments of soil moisture conditions correlate well with soil moisture retrievals from the NASA SMAP mission. This consistency allows for combining the two different types of data to produce a value-added assessment, which enables cropland soil moisture mapping and state-level statistics. Moreover, it enables daily assessment rather than weekly. The results signify that the SMAP SM retrievals are relatable to SM estimation conducted in agricultural crop land by land managers and farmers, which underlines the general applicability of the SMAP data.

The L-band active radar component of SMAP failed 2.5 months into the mission's operation, thereby leaving a higher resolution soil moisture data gap. One of the feasible approaches to fill this gap was to substitute the SMAP radar with other available SAR data. Das *et al.*, 2019 ([Remote Sensing of Environment](#)) published their derivation and evaluation of an algorithm to provide high resolution (1 km and 3 km) soil moisture data using data from the NASA SMAP mission and the ESA Sentinel-1 mission. This was a previously unmet goal of the SMAP mission due to the loss of the SMAP radar early in the mission. Despite some significant differences between the data from the Sentinel-1 satellites and the defunct SMAP radar, including operating frequency, Sentinel-1 data was found suitable for combining with the SMAP radiometer data because of its nearly similar orbit configuration that allows overlapping of their swaths with a minimal time difference, a key requirement for the SMAP active-passive algorithm. The substitution of

the Sentinel-1 data unfortunately degrades revisit time from 3 days to 12 days. Data can be found at: [https://nsidc.org/data/SPL2SMAP\\_S](https://nsidc.org/data/SPL2SMAP_S)

### ***Groundwater***

Measuring groundwater is challenging in localized basins, let alone on global scales. There are currently two remote sensing approaches for measuring and tracking changes in groundwater. Interferometric Synthetic Aperture Radar (InSAR) measures the surface deformation associated with the natural anthropogenic withdrawal and recharge/injection of water. Water volume is then obtained by modeling the surface deformation. Data from GRACE and GRACE-FO provides global measurements of mass change, including the redistribution of water (solid and liquid). Both techniques measure changes in water storage and not the absolute volume. The following set of publications utilize an array of measurement techniques (GRACE, InSAR, GPS) to better characterize and understand groundwater processes.

The flow of fresh groundwater to the ocean through the coast (fresh submarine groundwater discharge or fresh SGD) plays an important role in global biogeochemical cycles and coastal water quality. Zhou et al., 2019 ([Geophysical Research Letters](#)) provide the first near-global, high-resolution estimate of fresh submarine groundwater discharge (SGD) through the coastal zone to the ocean. These discharges play an important role delivering dissolved elements from land to sea, and form a natural barrier against salinization of coastal aquifers. The data shows that the distribution of fresh SGD is highly influenced by climate, with concentrated outflows at wet equatorial and high latitudes and gaps at dry midlatitudes. Large population centers in these dry latitudes are vulnerable to aquifer salinization and must manage groundwater extraction carefully to avoid passing tipping points. The research results can be used to inform new science on our coastal water resources leading to valuable information for management of these resources.

Variability in climate and weather in many land regions is dominated by a seasonal cycle that is typically defined by a stable, repeated pattern. Defining the annual cycle as strictly stationary, however, precludes the possibility of changes in its amplitude from one year to the next. Hamlington *et al.*, 2019 ([Geophysical Research Letters](#)) used GRACE terrestrial water storage data from 2003 through 2017 to extract the amplitude variations of the annual water cycle for global land regions. In many locations, a trend is observed in the amplitude of the seasonal signal, although further analysis is required to determine if these trends are representative of a long-term change or simply an artifact of the short record. The authors found that climate variability is a dominant driver of the strength of the annual cycle in terrestrial water storage, with El Niño-Southern Oscillation found to play a particularly significant role, as identified in previous studies.

California's Central Valley is one of the major food production regions in the world where municipality and agricultural needs rely heavily on groundwater resources. Liu *et al.*, 2019 ([Geosciences](#)) observed strong correlation between NASA GRACE mission satellite groundwater anomaly (GWA) variation data and subsidence measured using ESA Sentinel-1 data in the Central Valley. The long-term subsidence record showed

clear slowdown/cessation in the winter of 2016–2017, the second wettest rainy season on record, which likely reflects a basin-wide response of a compacting aquifer system to the increase in water recharge and decrease in groundwater pumping. The research indicates that subsidence measurement from satellite data is a very useful indicator for tracking groundwater storage change. Research results also suggest that the GRACE data could potentially be combined with subsidence measurements from satellite data for improved groundwater storage estimates at fine resolution.

Separating recoverable (elastic) from permanent (inelastic) deformation of aquifer systems is critical to develop sustainable pumping practices but remains a challenge because the preconsolidation stress is unknown. Previous works often assume that inelastic deformation occurs over years while elastic deformation is seasonal. Chaussard and Farr, 2019 ([Geophysical Research Letters](#)) demonstrate a method for separating elastic from inelastic deformation of aquifer systems. The authors applied their method, known as Independent Component Analysis (ICA) to 2015–2019 Interferometric Synthetic Aperture Radar measurements of deformation in the San Joaquin Valley and showed that elastic deformation is always present and measurable by ICA along with longer-term deformation seen in both seasonal patterns and post drought recovery. The ability to separate recoverable from permanent deformation of aquifer systems can provide important information for developing sustainable pumping practices.

An innovative approach to track mass change and elastic (recoverable) deformation associated with the movement of water through surface/subsurface reservoirs outlined in the studies above is to utilize GPS/GNSS time series to track the elastic response of the Earth's surface related to regional and local loading signals arising from hydrologic mass transfer (i.e. seasonal/annual snow, rainfall, groundwater). Knappe *et al.*, 2020 ([Water Resources Research](#)) present results of a new method of separating the regional and local contributions of the elastic response of the Earth due to hydrologic mass transfers and show that GPS measurements are capable of measuring the local hydrologic load changes at watershed scales of tens of kilometers. The authors conclude that GPS time series data have high potential for use in monitoring hydrologic budgets at scales useful for water management and for assessment of the hydro-ecological response to climate change.

### **Water – Ecosystem / Evapotranspiration / Drought**

WEC seeks to better understand the two-way interactions between the hydrosphere and ecosphere. The availability of water for life encompasses the water supply, which includes the timing, magnitude, duration, and storage capabilities of the water (groundwater, soil moisture, surface water, snow, ice melt), as well as the water quality and the influence of water on the geomorphology. The vegetation water content of ecosystems is a living water reservoir which contributes to moving water through the global water and energy cycles through evapotranspiration (ET). Furthermore, anthropogenic activities such as agriculture production contribute to the movement of water through the global water budget and energy cycles. We highlight a pair of ET studies, a study that looks at vegetation water content in agriculture, and a study that begins to quantify hydrological droughts.

Pascolini *et al.*, 2020 ([Water Resources Research](#)) compared basin scale ET estimates from five land surface models and three remote sensing products against estimates derived from GRACE observations for eleven major river basins in the contiguous United States. Both the land surface model-based and remote sensing-based evapotranspiration (ET) were found to be persistently lower than the GRACE-based ET in all eleven basins tested. They also found that interannual variability is greater for GRACE-ET than for the model and remote sensing products, and this was attributed to precipitation variability. Evaluating basin-scale ET estimates using GRACE-based ET has high potential to inform the development of ET products from land surface models and remote sensing data, which are important data sources for water resource management.

Javadian *et al.*, 2020 ([Remote Sensing](#)) showed that while evapotranspiration has not changed significantly during the 2001 - 2018 study period across global natural lands, it has significantly increased across global croplands. The authors introduced a new index based on a combination of actual evapotranspiration (AET), potential evapotranspiration (PET), and precipitation rate (PP) estimates—the evapotranspiration warning index (ETWI) — which they used to evaluate the sustainability of observed AET trends. A high negative ETWI for a region could be unsustainable and lead to drought conditions because the outputs from the affected region would be more than the input to it. The high negative average ETWI for global croplands is largely driven by an extreme trend in AET, exceeding both PET and PP trends. Averaging cropland ETWI trends at the country level further revealed unsustainable trends in cropland water consumptions in Thailand, Brazil, and China.

Vegetation water content (VWC) is an important land surface parameter that is used in retrieving surface soil moisture from microwave satellite data. Cosh *et al.*, 2019 ([J. of Applied Remote Sensing](#)) described the results of field experiments conducted in northern central Iowa and southern Manitoba to improve estimates of VWC to improve performance of the SMAP soil moisture products for these intensive agricultural regions. Landsat 8 data was used to compute a normalized difference water index for the entire summer of 2016 that was then integrated with extensive VWC ground sampling to develop equations for improved, crop-specific, daily estimates of VWC for improved soil moisture retrieval. Future implementation of these equations into operational algorithms is expected to improve the overall performance of soil moisture retrievals in agricultural domains.

Drought is a global phenomenon that can have substantial impacts on regional ecosystems and water availability that drive economies, therefore, the ability to quantify the severity of droughts will help understand and correlate droughts around the world. Zhao *et al.*, 2019 ([Geophysical Research Letters](#)) introduced a framework for monitoring hydrological droughts using a global, long-term, monthly, remotely sensed reservoir surface area dataset. The authors developed a new index – the reservoir area drought index (RADI) – defined as the monthly normalized reservoir area time series. RADI was validated using an in situ reservoir storage based index. RADI not only helps to characterize drought propagation from meteorological and agricultural droughts to

hydrological droughts but also fills the information gap between streamflow/runoff-based and groundwater-based drought indices. The reservoir surface area dataset was further used to characterize the recovery rate (and to estimate the recovery time) at the individual reservoir scale during droughts. This across-scale drought monitoring framework can provide information to help mitigate drought impacts and increase water use efficiency among multi-reservoir systems.

### **Section 1.1.8.6 Weather and Atmospheric Dynamics Focus Area**

The Weather and Atmospheric Dynamics Focus Area (WAD; <https://science.nasa.gov/earth-science/programs/research-analysis/earth-weather>) uses NASA's existing fleet of satellites to take observations of weather systems, produces carefully calibrated data products for scientific investigations including characterization, understanding, prediction and applications, develops new observation platforms and instruments to expand the observations, performs field campaigns to understand the weather producing processes, studies the behavior of weather systems using integrated modeling and data assimilation systems, and transitions the scientific understanding and knowledge to operational weather forecast organizations.

To demonstrate progress in **characterizing the behavior of the Earth system, including its various components and the naturally-occurring and human-induced forcings that act upon it**, the WAD supports calibration and product generation for weather and atmospheric dynamics related parameters (precipitation, atmospheric temperature and humidity profiles, atmospheric winds, and ocean surface winds). WAD funds scientific investigations that analyze the data products to characterize the behavior of the Earth system with emphasis on phenomena identified in satellite observations. Two of the major long-term environmental data sets developed for the research communities highlighted in this report are the Integrated Multi-SatellitE Retrievals for GPM (IMERG) and Community Long-Term Infrared Microwave Combined Atmospheric Product System (CLIMCAPS). These community data sets are addressing the weather research and development communities' needs for data analysis and for comparison to modeling results. While IMERG is a long-term global precipitation data set, the CLIMCAPS is a long-term atmospheric state data.

#### *Characterizing Ocean and Land Surface Parameters:*

Cyclone Global Navigation Satellite System (CYGNSS) measurements of GPS signal reflectivity over ocean and land have been used to characterize components of the Earth system, to understand its controlling processes, and to improve our ability to predict its development. Over ocean, its measurements of hurricane winds produce improved storm center location fixes (Mayers and Ruf, 2019). Its tropical wind speed and surface flux products are used to examine important surface flux feedbacks that can destabilize the Madden-Julian Oscillation (Crespo et al. 2019; Maloney, 2019). Over land, CYGNSS is able to map changes in volumetric soil moisture content (Al-Khaldi et al., 2019; Chew and Small, 2019; Clarizia et al., 2019) and produce flood inundation maps (Morris et al., 2019). Imaging of inland water extent has also been used to measure river flowrate via changes in river width (Warnock and Ruf, 2019) and produce high resolution watermasks and flood maps for long-term hydrologic studies (yearly maps), seasonal hydrological studies, and near-real time identification of flooded areas (Gerlein-Safdi and Ruf, 2019).

#### *Characterizing the Behavior of the Atmosphere:*

Atmospheric Infrared Sounder (AIRS) v7 Data Release: On July 20th, 2020, the AIRS Version 7 of the L2 and L3 data products was released to the public. This was a coordinated effort of the AIRS Science Team, the AIRS project and software integration

team, and the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC). The Version 7 data products represent a significant improvement over the previous Version 6 products, especially with the AIRS "infrared-only" product (Yue et al., 2020). Notable improvements include: improved consistency between day and night water vapor; improved total column ozone; improved temperature products; improved AIRS IR-only retrievals, especially in the high latitude regions; improved Stochastic Cloud Clearing Neural Network (SCCNN) which is used as a first guess; removal of ambiguity in surface classification in the infrared-only (IR-only) retrieval algorithm. WAD anticipates this data product will be used in the future for improving characterization of the behavior of atmospheric processes.

Long-term atmospheric state data record development: CLIMCAPS Version 2 was successfully delivered to and implemented at the GES DISC and its sounding retrievals and cloud cleared radiance products are available to the public for the full Suomi-NPP and NOAA-20 records (Barnet 2019a, 2019b). CLIMCAPS/Aqua has also been delivered and should be operational at GES-DISC in 4QFY20. CLIMCAPS for AIRS/AMSU and CrIS/ATMS is the NASA Sounding continuity product and we published a characterization of its information content and uncertainty in (Smith and Barnet 2019, 2020) to demonstrate its observing capability across time and space. We established collaboration with scientists in air chemistry modeling and long-term monitoring at NOAA/ESRL/GML and NASA/GSFC with the purpose to evaluate and assimilate CLIMCAPS CO and O<sub>3</sub> retrieval products. This sounder team participated in the GES DISC Users Working Group to help improve data product accessibility and public outreach and have written a series of CLIMCAPS product application guides (Smith et al. under review) to bridge the gap between technical documentation and peer review publications. These product application guides will be available on-line in late 2020 at the GES DISC and NASA JPL and will help ensure that CLIMCAPS products can more readily contribute to NASA weather and climate applications.

Algorithm to fuse multiple instrument radiance observations: The goal of this work is to produce a homogeneous, gridded, radiance data set over several decades that converts high resolution AIRS, CrIS and IASI radiances to a common spectral response, and to use these climate-quality data to answer several fundamental climate questions. Science topics include: (1) the magnitude of water-vapor feedback as observed over several decades, (2) trends in cloud longwave fraction and radiative forcing, and (3) trends in both air and surface temperature. This homogeneous radiance dataset provides measurements similar to a long-wave CLARREO mission, but with different space/time sampling. Recent progress includes (1) establishment of the radiance offsets between AIRS and CrIS and IASI, (2) completion of the algorithm to produce this data set (Strow and DeSouza-Machado 2020) with submission to the Sounder SIPS for integration at the GSFC DIS, and (3) development of a retrieval approach (using radiance anomalies) for these data that has established the stability of AIRS radiances to an accuracy of ~0.02K/decade by comparing retrieved CO<sub>2</sub> anomaly trends to in-situ Cs<sub>2</sub> trends from NOAA/ESRL.

Atmospheric motion vector winds algorithm development: A 3D winds product is developed by tracking moisture features (troposphere) and ozone gradients (stratosphere) from AIRS retrieved vertical profiles of temperature, humidity, and ozone in the polar regions. Several detailed studies were conducted this year to investigate the sources of uncertainty in feature-tracked winds which will produce robust estimates of the uncertainty in the 3D wind retrievals, needed for improved assimilation and forecast impact in global numerical models (Santek et al. 2019, Posselt et al. 2019). Comparisons between co-located AIRS 3D winds and ESA's Aeolus Doppler Wind Lidar (DWL) Rayleigh winds exhibit a high correlation and we anticipate that the hyperspectral IR retrieval winds will have a high positive impact in data assimilation for high-latitude regions.

Advanced microwave sounding algorithm development: A member of the sounders science team completed the development of the ATMS system called "Retrieval Algorithm for Microwave Sounders in Earth Science" (RAMSES). It is currently undergoing testing in the Sounder SIPS and is expected to be delivered to GES DISC in the near future for public release and production. RAMSES is NASA's only stand-alone ATMS retrieval system and will be used to process data from a variety of NASA and NOAA platforms, including current and future JPSS satellites and are especially useful for parameters such as water vapor and temperature but also precipitation and surface characteristics. A sensitivity study was carried out that reveals enhanced PBL water vapor sensitivity in the 125-165 GHz part of the spectrum. This can be used to inform the design of future sensors and was presented at the 2019 Fall AGU meeting (poster Stumbaugh et al. 2019 AGU, A11T-2818).

Use of hyperspectral sounders to study PBL: A scientist reviewed the current state of hyperspectral IR and microwave sounding of the planetary boundary layer (PBL), and developed a coupled machine learning approach with a second pass physical retrieval algorithm for water vapor, with the goal of improving vertical resolution versus existing approaches by testing new families of a-priori constraints to preserve sharp "edge" features near the surface. The retrievals were evaluated using Southern Great Plains (SGP) sonde data from the 2015 "Enhanced Soundings for Local Coupling Studies" (ESLCS) campaign spanning 06/2015 to 08/2015. The preliminary results from the new algorithm generally look vertically sharper, including significantly more accurate determination of PBL height, as well as better representation of other vertical features such as moist tongues missed by the existing AIRS/AMSU L2 retrieval algorithm. While these initial improvements are encouraging, more validation on multiple years of datasets is underway.

*Better Characterization and Understanding of Convective Cloud and Precipitation:*

Use of IMERG to study extreme precipitation: Extreme precipitation events have the potential to create catastrophic flooding, landslides, and infrastructure damage. Zhou et al. (2019) diagnosed the spatial and temporal characteristics of such events using Integrated Multi-Satellite Retrievals for GPM (IMERG) precipitation estimates to construct a record of extreme events that depict both the spatial extent and evolution of precipitation systems. They developed a classification approach that enables the accurate

depiction of duration, areal coverage, total volume, and propagation of each extreme event over its entire life cycle. Results from four years of IMERG statistics over the contiguous United States show that the most frequent extreme events have duration between 3 – 6 hours, an affected area of 1000 – 50,000 km<sup>2</sup> and a total precipitation volume of 10<sup>6</sup> – 10<sup>8</sup> m<sup>3</sup> (enough to fill ~2 to 176 Rose Bowl stadiums). These events occur most frequently in the Northwest and Northeast U.S. in winter and spring, and the Southwest and Southeast in summer. Fall has the least number of extreme events and summer exhibits some of the heaviest and largest events.

Characterizing hailstorms: Mroz et al. (2020) performed a statistical analysis of simultaneous observations of more than 800 hailstorms over the continental United States using GPM DPR data and the ground-based radar network. They identify several distinctive features in DPR measurements for hail-bearing storms that are potentially exploitable by hydrometeor classification algorithms. In particular, the height and the strength of the Ka-band reflectivity peak show a strong relationship with the hail shaft area. However, multiple scattering and non-uniform beam filling (variations in precipitation properties on scales smaller than the instrument footprint) introduce ambiguities for hail detection and rainfall retrieval. The shapes of the DPR reflectivity profiles are the result of the complex interplay between the scattering properties of the different hydrometeors (different types of ice particles including snow and hail), non-uniform beam filling, and multiple scattering effects, which significantly reduces the ability of the DPR instrument to detect hail at the ground.

Correlate hail observation to damages on the ground: Large hail is a major contributor to storm damage around the world in terms of both agriculture and infrastructure. The scattering signatures of hail in passive microwave radiometer measurements led to the development of proxies for severe hail. Using 16+ years of data from the Tropical Rainfall Measuring Mission (TRMM;), Bang and Cecil (2019) pair TRMM observations with surface hail reports in the United States to train a hail retrieval algorithm. They then apply this hail retrieval to data from GPM to develop a nearly global passive microwave-based climatology of hail. Their results show that the highest hail frequencies occur in the region of northern Argentina through Paraguay, Uruguay, and southern Brazil; in the central United States; and in a portion of central Africa. A notable difference between Bang and Cecil's results and those found in prior satellite-based studies is that central Africa, while still active, does not rival the aforementioned regions in detected hailstorm frequency.

Characterizing diurnal cycle of rainfall using IMERG: Tan et al. (2019) demonstrate the maturing ability of half-hourly IMERG precipitation estimates to characterize the diurnal cycle of rainfall. Refined intercalibration and interpolation between satellite observations leads to greater consistency in the precipitation retrievals over different hours of the day. Evaluation against ground measurements suggests only a slight lag in the diurnal phase (about half an hour). The diurnal cycle over different regions around the globe was demonstrated, including the Maritime Continent, where accurate representation of precipitation variability in global models remains a challenge. Using examples over

several regions, they reveal the intricate interplay between diurnal and seasonal variability.

Measuring precipitation particle properties: The GPM-DPR has provided a unique opportunity to investigate precipitation particle properties. Chase et al. (2020) conducted an evaluation of the microphysical framework used within the GPM-DPR retrieval using ground-based disdrometer measurements in both rain and snow with an emphasis on the evaluation of GPM's snowfall retrieval algorithm. Disdrometer measurements for rain show support for the two separate prescribed relationships between precipitation rate and mass-weighted mean diameter ( $D_m$ ) used within the GPM-DPR algorithm. Ground-based disdrometer measurements for snow show higher error and bias in the retrieval of snowfall rate compared to the stratiform rain relation. An investigation using the disdrometer-measured fall velocity and mass in the calculation of precipitation rate and particle size illustrates that the variability found in hydrometeor mass causes a poor correlation between these parameters in snowfall. The results suggest that the retrievals are likely not optimal in snowfall and other retrieval techniques for precipitation rate should be explored.

Study of winter precipitation: Pettersen et al. (2020) present data from four winter seasons from an enhanced precipitation instrument suite based at the National Weather Service (NWS) Office in Marquette (MQT), Michigan, which receives 250–500 cm of annual snow accumulation. Observations are used to partition large-scale synoptically driven (typically deep) and surface-forced (typically shallow) snow events and highlight different characteristics with respect to snow event category. Shallow snow events are often extremely shallow, with radar-indicated heights of less than 1.5 km above ground level. Large vertical reflectivity gradients indicate efficient particle growth and increased aggregation in shallow snow events. Shallow snow events occur twice as often as deep events; however, both categories contribute nearly equally to estimated annual accumulation. Microphysical measurements reveal distinct regime-dependent differences in microphysical properties, with shallow snow events having broader particle size distributions and comparatively fewer small particles and deep snow events having narrower particle size distributions and comparatively more small particles.

Characterizing winter precipitation snow fall rates in observations: Information on falling snow derived from space-based observations are important for understanding linkages between Earth's atmospheric, hydrological, and energy cycles. Skofronick-Jackson et al. (2019) quantified and investigated causes of differences between snowfall estimates from the GPM's Dual-frequency Precipitation Radar and from CloudSat's Cloud Profiling Radar (CPR). Important challenges arise from different snow–rain classification methods, satellite orbits, instrument resolutions, sampling, instrument specifications, and algorithm assumptions. After equalizing for several factors, CPR and DPR observed similar snowfall occurrences while CPR observed about 43% higher average snowfall rates, indicating that retrieval assumptions (microphysics and snow scattering properties) are quite different. CPR–DPR snowfall amount differences were reduced to ~16% after accounting for differences in retrieval assumptions.

Trends of high-latitude convective storms in the warming world: Over the last century, North Hemisphere high-latitude land regions, particularly Siberia, northern Europe, and northern Canada, have experienced the largest surface temperature increases on Earth. Observations from GPM's DPR radar (Houze et al. 2019) are showing that extreme convective storms are occurring in these high-latitude continental regions. Five years of GPM data on the 3-D structure of these storms suggest that these storms often occur during the warm season in high-latitude continental regions where the increase of surface temperature has been greatest, while data on the thermodynamic environment suggests that these storms could be more common in a future warming world.

Examine the properties of the cores of deep convection: Using three years of observations from the DPR, Ni et al. (2019) examine the properties of the cores of deep convection. The deep convective cores are described in terms of the profiles of Ku- and Ka-band radar reflectivity at the location of the highest echo top in each deep convective storm. Using dual-frequency ratios (DFR) profiles, derived by subtracting Ka-band from Ku-band radar reflectivity, they find that DFR values are larger over land than over ocean in general near the top of the convection, consistent with larger ice particles in stronger updrafts in continental convection. The magnitude of DFR at upper levels is positively correlated with convective intensity. The cores of deep convective systems over land generally have larger ice particle sizes, higher ice water contents, and lower particle concentrations than those over the ocean, but with some distinct regional variations.

Characterizing the orographic microphysical processes: Arulraj and Barros (2019) present a physically based framework to address errors in Quantitative Precipitation Estimates (QPE) from the GPM DPR in regions of complex terrain. GPM precipitation estimates are evaluated against ground validation (GV) observations in the Southern Appalachian Mountains. The errors exhibit a diurnal cycle consistent with the diurnal cycle of low-level clouds and fog, suggesting the importance of low-level orographic microphysical processes. They suggest that seeder-feeder interactions (higher level clouds seeding precipitation growth in lower level clouds) can be intimately tied to the cloud microphysics and ultimately to the estimation of precipitation in orographic regions.

Lightning in winter precipitation: Thundersnow events are identified when lightning occurs in conjunction with a surface temperature colder than 0°C and when the entire vertical temperature profile is below 2°C. Using 4 years of observations from the GPM Ku-band radar as well as national lightning network data and NASA global reanalyses, Adhikari and Liu (2019) identify 443 thundersnow features, indicating the relative rarity of these events. The majority of these features (about 394) were found over high mountainous regions such the Himalayas, Tibet, the Andes, and the Zagros mountain regions. Lower elevation thundersnow events (45) were observed over land and in coastal regions. Although only a small number of thundersnow features are identified with 4 years of GPM data, most thundersnow events have maximum radar reflectivity above 30 dBZ at temperature colder than -10 °C, indicating that the noninductive charging process is important in these events.

**High Temporal Environmental Monitoring and Characterization**

Use of geostationary infrared imaging for monitoring weather: With the transition of multispectral imagery from the Advanced Baseline Imager (ABI) from the GOES-16 and GOES-17 weather satellites to operational forecasters at the NOAA National Weather Service (NWS) SPoRT (the Short-term Prediction Research and Transition program) provided scientific guidance to NOAA NWS on the operational implementation of multispectral composites guiding technical implementation of SPoRT developed capabilities and improved, scientifically valid techniques to provide high-quality imagery to all forecasters across NOAA NWS. In addition SPoRT has developed a technique for limb correction of geostationary RGB imagery in clear and cloudy regions to improve interpretation of RGB composites at oblique satellite view angles (Elmer et al. 2019). Limb-corrected RGB composites enable atmospheric features on the limb to be correctly interpreted by operational forecasters, since they enable more accurate interpretation of atmospheric features due to improved RGB coloring.

Apply GLM observations in emergency management: SPoRT has contributed to the transition of Geostationary Lightning Mapper (GLM) observations from the GOES-16 and GOES-17 weather satellite to operational forecasters at the NOAA National Weather Service (NWS) and emergency management staff at NASA MSFC (Stano et al. 2019). The team continues to work collaboratively with NOAA and other operational users to develop common web and software displays through a NOAA Joint Technology Transfer Initiative (JTII) to incorporate GLM data into day-to-day operations, as well as, the development of new products to diagnose the intensity of convection and provide lightning risk metrics for lightning safety applications (e.g., Stano et al. 2019). SPoRT also disseminates GLM level-2 and 3 products in real time to NASA Partners, including NASA Goddard, Langley, and Ames using the GOES-R Receiving Station located at MSFC.

Development of weather forecast product and training materials: SPoRT has been part of a multi-agency and multi-organizational effort to develop the capability to grid and view satellite soundings as plan view displays in the NOAA NWS operational display system and conduct applied research studies to demonstrate new applications. The capability was released to the NOAA NWS during FY19 and operations to research feedback has driven its development (Esmaili et al 2020). SPoRT has engaged new stakeholders in the fire weather community to use S-NPP and NOAA-20 CrIS/ATMS and has completed development of web-visualizations to support new applications and end users beyond NWS end users. These activities included development of [targeted training](#) for fire weather analysis and collaborating with JPSS and other cooperative institutes to develop satellite training for NWS Incident Meteorologists.

GPM imagery product for weather forecast operations: SPoRT has developed and tailored GPM imagery and precipitation products to support operational weather forecasting and hydrology. Key GPM Early Adopter activities to introduce GPM data products to NWS forecasters and hydrologists have been published in the Springer Satellite Precipitation Measurement book (LeRoy et al. 2020). As a GPM Early Adopter

## Management and Performance: FY 2020 Annual Performance Report

SPoRT's research-to-operations/operations-to-research paradigm and interaction with end users and algorithm developers lead to prioritizing algorithm improvements to benefit the operational community and improve the science-quality of the observations.

Characterizing and monitoring severe drought: SPoRT has engaged with a series of stakeholders within the drought monitoring community through the transition of the Evaporative Stress Index (ESI; Zhong et al. 2020; Kang et al. 2020). ESI is available operationally at the National Drought Mitigation Center, which is responsible for issuing the weekly U.S. Drought Monitor. A new global ESI product developed at NASA SPoRT and through a partnership with NASA-SERVIR, the experimental near-real-time global ESI products have made available to all SERVIR hubs through their cloud-based ClimateSERV platform.

**Annual Performance Goal 1.1.9: NASA shall demonstrate progress in enhancing understanding of the interacting processes that control the behavior of the Earth system, and in utilizing the enhanced knowledge to improve predictive capability.**

**Section 1.1.9.1 Atmospheric Composition Focus Area**

For demonstrating progress in **enhancing understanding of the interacting processes that control the behavior of the Earth system, and in utilizing the enhanced knowledge to improve predictive capability**, ACFA sponsored research in FY2020 to (a) elucidate interactions between aerosols and the formation of clouds, diagnose distant sources of dust, and reduce biases in models using cloud complementary satellite observations; (b) more fully characterize spatial and temporal variability of pollution on regional scales and distinguish between natural and anthropogenic effects, each in the service of improved weather and air quality forecasts; (c) better describe the processes that influence the production and loss processes controlling NO<sub>x</sub>, CO, isoprene and the influence of volatile organic compounds (VOCs); and (d) use both satellite observations and large-scale models to understand the chemical processes that control the pace of ozone recovery, now and in the decades to come. Finally, ACFA field missions buttressed satellite observations and modeling studies with observations to address a range of issues such as the possible role for plankton in formation of salt spray aerosol, PM<sub>2.5</sub> variability and the role of VOCs in formation of ozone in urban settings.

***A. Aerosol and cloud radiative effects research***

***Cloud physics from space***

In an invited paper, Stephens et al. (2019) reviewed the progression of cloud physics from a subdiscipline of meteorology into the global science that it is today. The review is centered on the properties of warm clouds and the connection between the early contributions to cloud physics to the current vexing problem of aerosol effects on cloud albedo. Progress toward estimating cloud properties from space and insights on warm cloud processes are described with many examples from ACFA-sponsored research. Measurements of selected cloud properties, such as cloud liquid water path are now mature enough that multi-decadal time series of these properties exist, and this climatology is used to compare to analogous low-cloud properties taken from global climate models. The too-wet (and thus too bright) and the too-dreary biases of models are called out, underscoring the challenges we still face in representing warm clouds in Earth system models. The authors also provide strategies for using observations to constrain the indirect radiative forcing of the climate system.

***Distinct Impacts of Increased Aerosols on Cloud Droplet Number Concentration of Stratus/Stratocumulus and Cumulus***

Aerosol-cloud interactions have the largest uncertainty in assessing the anthropogenic contribution to present and future climate change. There still exist large differences in aerosol indirect radiative forcing between the satellite-based and model-based studies. Moreover, recent satellite-based studies have suggested that an increase of aerosols may reduce the cloud droplet number concentration over land, which is contrary to the conventional aerosol indirect effect. This discrepancy might be subject to the inherent limitations of satellite retrieval. To address this question, Jia *et al.* (2019) used detailed *in situ* measurements to investigate the impacts of aerosol on continental stratocumulus and cumulus clouds. They found that with increasing cloud condensation nuclei, cloud droplet number concentration ( $N_d$ ) increases for stratocumulus but exhibits only a negligible change for cumulus. The analysis shows that neither the simultaneously changing cloud dynamics nor entrainment-mixing can explain the observed insensitivity of  $N_d$  in cumulus. The difference between stratocumulus and cumulus is likely caused by the different degree of reduction in cloud supersaturation caused by increasing aerosols. This finding improves the understanding on aerosol effects on different cloud regimes and should lead to more accurate estimates of first indirect radiative forcing from both observation and model.

*Regional biases in MODIS marine liquid water cloud drop effective radius deduced through fusion with MISR*

The effective radius ( $R_e$ ) of the cloud drop size distribution plays an important role in the energy and water cycle of the Earth. Satellite measurements from Terra MODIS represent our longest global record of  $R_e$ ; however, known biases ranging from  $\sim 2 \mu\text{m}$  ( $\sim 20\%$ ) to  $\sim 9 \mu\text{m}$  ( $\sim 50\%$ ) in regional monthly-mean values have been attributed to cloud heterogeneity and Sun angle effects. Fu *et al.* (2019) demonstrated that estimation and correction for these biases is achieved by fusing MODIS data with multi-angular observations from MISR, also flying on Terra. The bias-corrected  $R_e$  values compare favorably to independent data sources including field observations; the results are significant as they can impact assessments of aerosol-cloud interactions and cloud parameterizations in climate models.

*Disproving the Bodélé Depression as the primary source of dust fertilizing the Amazon Rainforest*

North African deserts supply nutrients to fertilize the Amazon Rainforest in boreal winter and spring through transatlantic transport. While previous studies argued that the Bodélé depression is the main contributor, these claims have not been supported by geochemical analysis. Motivated by this ongoing debate, Yu *et al.* (2020) used dust plume heights and motion speeds from the MISR Cloud Motion Vector Product, MISR and MODIS dust aerosol optical depths, CALIOP dust vertical profiles from, and TRMM precipitation patterns to constrain a trajectory analysis. The paper reached the novel conclusion that the El Djouf desert is the preferred source of intercontinental transport to the Amazon Basin and Caribbean Sea, rather than the Bodélé depression.

***B. Air quality research***

*Disentangling the impact of the COVID-19 lockdowns on urban NO<sub>2</sub> from natural variability*

Goldberg *et al.* (2020) used satellite data to analyze substantial drops in nitrogen dioxide (NO<sub>2</sub>) observed during COVID-19 physical distancing. Attribution of NO<sub>2</sub> changes to NO<sub>x</sub> emissions changes over short timescales must take into account that variations in meteorological conditions year-to-year variations can cause column NO<sub>2</sub> differences of ~15% on monthly timescales. In the spring of 2020 meteorological patterns were especially favorable for low NO<sub>2</sub> in much, complicating comparisons with spring 2019. After accounting for sun angle and meteorological considerations, they calculated that NO<sub>2</sub> drops ranged between 9.2–43.4% among twenty cities in North America, with a median of 21.6%. Of the studied cities, the largest NO<sub>2</sub> drops (>30%) were in San Jose, Los Angeles, and Toronto, and smallest drops (<12%) were in Miami, Minneapolis, and Dallas. These normalized NO<sub>2</sub> changes can be used to highlight locations with greater activity changes and better understand the sources contributing to adverse air quality in each city.

*Satellite data reveal a common combustion emission pathway for major cities in China*

Extensive fossil fuel combustion in rapidly developing cities severely affects air quality and public health. Tang *et al.* (2019) reported observational evidence of decadal changes in the efficiency and cleanness of bulk combustion over large cities in mainland China. In order to estimate the trends in enhancement ratios of CO and SO<sub>2</sub> to NO<sub>2</sub> and infer emergent bulk combustion properties over these cities, they combined air quality retrievals from widely used satellite instruments over the 2005–2014 period, including MOPITT. They presented results for four Chinese cities (Shenyang, Beijing, Shanghai, and Shenzhen) that represent four levels of urban development. The results show a robust coherent progression of declining to growing  $\Delta\text{CO}/\Delta\text{NO}_2$  relative to 2005 across the four cities. Importantly, the coherent progression they find is not evident in the trends of emission ratios reported in Representative Concentration Pathway (RCP8.5) inventory. This progression is likely due to a shift towards cleaner combustion from industrial and residential sectors in Shanghai and Shenzhen that is not yet seen in Shenyang and Beijing. This overall trend is presently obfuscated by China's still relatively higher dependence on coal. Such progression is well-correlated with economic development and traces a common emission pathway that resembles evolution of air pollution in more developed cities. Their results highlight the utility of augmenting observing and modeling capabilities by exploiting enhancement ratios in constraining the time variation in emission ratios in current inventories. As cities and/or countries continue to develop socioeconomically, the ability to monitor combustion efficiency and effectiveness of pollution control becomes increasingly important in assessing sustainable control strategies.

*Enhancing accuracy of air quality and temperature forecasts during paddy crop residue burning season in Delhi via chemical data assimilation*

Kumar *et al.* (2020) examined the accuracy of Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) generated 72-hour fine particulate matter (PM<sub>2.5</sub>) forecasts in Delhi during the crop-residue burning season of October–November 2017 with respect to assimilation of the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth (AOD) retrievals, persistent fire emission assumption, and aerosol-radiation interactions. The assimilation significantly pushed the model AOD and PM<sub>2.5</sub> toward the observations with the largest changes below 5 km altitude in the fire source regions (northeastern Pakistan, Punjab, and Haryana) as well as the receptor New Delhi. A persistence fire emission assumption was found to work well, as the accuracy of PM<sub>2.5</sub> forecasts driven by persistent fire emissions was only 6% lower compared to those driven by real fire emissions. Aerosol-radiation feedback extended the benefits of assimilating satellite AOD beyond PM<sub>2.5</sub> forecasts to surface temperature forecast with a reduction in the mean bias of 0.9–1.5°C (17–30%). These results demonstrate that air quality forecasting can benefit substantially from satellite AOD observations particularly in developing countries that lack resources to rapidly build dense air quality monitoring networks.

*Direct observation of changing NO<sub>x</sub> lifetime in North American cities*

Laughner and Cohen (2019) used OMI observations of NO<sub>2</sub> from a new high-resolution product to show that NO<sub>x</sub> lifetime in approximately 30 North American cities has changed between 2005 and 2014 in a manner consistent with our understanding of NO<sub>x</sub> chemistry. NO<sub>x</sub> lifetime relates nonlinearly to its own concentration; therefore, by observing how NO<sub>x</sub> lifetime changes with changes in its concentration, inferences can be made about the dominant chemistry occurring in an urban plume. The authors saw significant changes in NO<sub>x</sub> lifetime in North American cities that are of the same order as changes in NO<sub>x</sub> emissions over the same time periods. The pattern of these changes suggests that NO<sub>x</sub>-limited chemistry dominates North American urban plumes and also demonstrates that the change in NO<sub>x</sub> lifetime must be accounted for when relating NO<sub>x</sub> emissions and concentrations.

*Sensitivity of meteorological skill to selection of WRF-Chem physical parameterizations and impact on ozone prediction during the Lake Michigan Ozone Study*

Ozone concentrations in excess of health-based standards occur along the coastline of Lake Michigan. A complex pattern of ozone precursor emissions interfaces with a complex meteorological environment, presenting a challenge for air quality management and simulation. Precursors are transported into a shallow, stable boundary layer over the lake. This is followed by ozone formation and transport back onshore through a combination of synoptic and lake breeze winds. Abdi-Oskouei *et al.* (2020) used measurements during the Lake Michigan Ozone Study 2017 (LMOS) to quantitatively evaluate the Weather Research and Forecasting with Chemistry (WRF-Chem) model at 4-km horizontal resolution for key features of high ozone episodes over Southern Lake Michigan, with a focus on meteorological performance. WRF-Chem showed good performance and successful reproduction of meteorological fields and clouds. Lake breeze model skill was inconsistent, with both good and poor performance depending on

site and day. The combination of the Noah land surface model and High-Resolution Rapid Refresh meteorology gave the best performance with a mean bias of  $-0.5^{\circ}\text{C}$  in temperature,  $-0.6^{\circ}\text{C}$  in dewpoint temperature, and  $-0.3\text{ m/s}$  in wind speed along the western coast of Lake Michigan during the daytime. For ozone, WRF-Chem was biased low ( $-4.4\text{ ppb}$  mean bias for daytime ozone) and underestimated hourly peak ozone. In some cases, ozone bias could be attributed to transport and lake breeze errors. Average ozone concentration showed minor ( $<2\text{ ppb}$ ) sensitivity to changes to meteorology initial and boundary conditions or the land surface model.

### *Understanding the emissions of $\text{NO}_x$ and VOCs based on ozone observations in the United States*

Surface ozone, which is produced by nitrogen oxides and volatile organic compounds in the daytime, adversely affects human health and vegetation growth. Observed ozone concentrations can be used to evaluate nitrogen oxides and volatile organic compound emissions by using their relationships with ozone concentrations. Li *et al.* (2019b) showed that the time when ozone reaches its daily maximum (peak time) is also related to nitrogen oxides and volatile organic compound emissions. They used a three-dimensional model to simulate ozone daily maximum concentrations (peak value) and peak time in July 2011 over the contiguous United States. Through model sensitivity analyses, they found that ozone peak values are more sensitive to nitrogen oxide emissions, while ozone peak time is more sensitive to volatile organic compound emissions in the eastern United States. By such relationships and the comparison between observations and model results, they found that the underestimation of soil nitrogen oxides emissions leads to a low bias of simulated ozone peak value in the south, while the overestimation of biogenic isoprene emissions results in earlier than observed ozone peak time in the central, south, and southeast regions. The simulated formaldehyde columns, which are higher than satellite measurements, confirm the latter.

### ***C. Tropospheric greenhouse and other trace gas research***

#### *Lightning $\text{NO}_x$ production efficiency*

Two papers (Bucsela *et al.*, 2019 and Allen *et al.*, 2019) estimated the production efficiency (PE) of lightning  $\text{NO}_x$  ( $\text{LNO}_x$ ) using satellite data from the Ozone Monitoring Instrument (OMI) and the ground-based World Wide Lightning Location Network (WWLLN) in three northern mid-latitude, primarily continental regions. Data were obtained over 5 boreal summers, 2007 – 2011 and comprise the largest number of mid-latitude convective events to date for estimating the  $\text{LNO}_x$  PE with satellite  $\text{NO}_2$  and ground-based lightning measurements. The authors infer an average value of  $180 \pm 100$  moles  $\text{LNO}_x$  produced per lightning flash. Better knowledge of  $\text{LNO}_x$  will improve confidence in the magnitude of production of ozone in the middle and upper troposphere, where the effect of ozone on radiative forcing of climate maximizes.  $\text{LNO}_x$  also influences OH concentrations, which play a major role in determining the lifetime of methane.

*New constraints on biogenic emissions from satellite-based estimates of carbon monoxide fluxes*

Biogenic non-methane volatile organic compounds (NMVOCs) emitted from vegetation are a primary source for the chemical production of carbon monoxide (CO) in the atmosphere, and these biogenic emissions account for about 18 % of the global CO burden. Worden *et al.* (2019) showed that partitioning CO fluxes among different source types in top-down inversion methods is challenging; typically, a simple scaling of the posterior flux to prior flux values for fossil fuel, biogenic and biomass burning sources is used. They showed top-down estimates of biogenic CO fluxes using a Bayesian inference approach, which explicitly accounts for both *a posteriori* and *a priori* CO flux uncertainties. This approach re-partitions CO fluxes following inversion of Measurements Of Pollution In The Troposphere (MOPITT) CO observations with the GEOS-Chem model, a global chemical transport model driven by assimilated meteorology from the NASA Goddard Earth Observing System (GEOS). They compared these results to the prior information for CO used to represent biogenic NMVOCs from GEOS-Chem, which uses the Model of Emissions of Gases and Aerosols from Nature (MEGAN) for biogenic emissions. They conclude that this method for estimating biogenic sources of CO will provide an independent constraint on modeled biogenic emissions and has the potential for diagnosing decadal-scale changes in emissions due to land-use change and climate variability.

*Convective Entrainment Rates Estimated from Aura CO and CloudSat/CALIPSO Observations and Comparison With GEOS-5*

Entrainment rate in convective parameterizations is one of the most sensitive, yet uncertain, parameters affecting models of climate sensitivity, clouds, precipitation, and trace gas distributions. Observational constraints on entrainment rate have typically come from *in situ* and/or field campaign observations, providing only limited insights into the global variability of entrainment. Using the joint retrieval of carbon monoxide (CO) from the Microwave Limb Sounder (MLS) and Tropospheric Emission Spectrometer (TES) instruments on NASA's Aura satellite, in conjunction with metrics of deep convection from NASA's CloudSat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) missions, Stanfield *et al.* (2019) quantified deep convective entrainment over the globe and compared the results with counterparts from NASA's GEOS-5 model. The study found a weak anticorrelation between entrainment and increasing Convectively Available Potential Energy (CAPE) and relative humidity, whereas the GEOS-5 model exhibits somewhat different relationships. The results serve as an important reference for improving convective parameterizations in climate models and constraining model simulations of deep convection.

*Satellite isoprene retrievals constrain emissions and atmospheric oxidation*

Isoprene is the dominant non-methane organic compound emitted to the atmosphere. It drives ozone and aerosol production, modulates atmospheric oxidation and interacts with the global nitrogen cycle. Isoprene emissions are highly uncertain, as is the nonlinear

chemistry coupling isoprene and the hydroxyl radical, OH—its primary sink. Wells *et al.* (2020) present global isoprene measurements taken from space using the Cross-track Infrared Sounder on the Suomi-NPP satellite. Together with observations of formaldehyde, an isoprene oxidation product, these measurements provide constraints on isoprene emissions and atmospheric oxidation. They find that the isoprene–formaldehyde relationships measured from space are broadly consistent with the current understanding of isoprene–OH chemistry, with no indication of missing OH recycling at low nitrogen oxide concentrations. They analyzed these datasets over four global isoprene hotspots in relation to model predictions and present a quantification of isoprene emissions based directly on satellite measurements of isoprene itself. A major discrepancy emerges over Amazonia where current underestimates of natural NO<sub>x</sub> emissions modeled OH and hence isoprene and over southern Africa, they find that a prominent isoprene hotspot is missing from bottom-up predictions. A multi-year analysis sheds light on interannual isoprene variability and suggests the influence of the El Niño/Southern Oscillation.

#### ***D. Upper atmospheric and ozone depletion research***

##### *Why Do Antarctic Ozone Recovery Trends Vary?*

Strahan *et al.* (2019) used satellite ozone records and Global Modeling Initiative (GMI) chemistry transport model (CTM) simulations integrated with Modern Era Retrospective for Research and Analysis 2 (MERRA2) meteorology to identify a metric that accurately captures the trend in Antarctic ozone attributable to the decline in ozone depleting substances (ODSs). The GMI CTM Baseline simulation with realistically varying ODS levels closely matches observed interannual to decadal scale variations in Antarctic September ozone over the past four decades. The expected increase or recovery trend is obtained from the differences between the Baseline simulation and one with identical meteorology and fixed 1995 ODS levels. The differences show that vortex-averaged column O<sub>3</sub> has the greatest sensitivity to ODS changes from 1 to 20 September. The observed vortex-averaged column O<sub>3</sub> during this period produces a trend consistent with the expected recovery attributable to ODS decline. Trends from dates after 20 September have smaller sensitivity to ODS decline and are more uncertain due to transport variability. Simulations show that the greatest decrease in O<sub>3</sub> loss (i.e., recovery) occurs inside the vortex near the edge. The polar cap metrics have vortex size-dependent bias and do not consistently sample this region. Because the 60-90°S 220 Dobson-unit O<sub>3</sub> mass deficit metric does not sample the edge region, its trend is lower than the expected trend; this is improved by area weighting. The 250 Dobson-unit O<sub>3</sub> mass deficit metric samples more of the edge region, which increases its trend. Approximately 25% of the September Antarctic O<sub>3</sub> increase is due to higher O<sub>3</sub> levels in June prior to winter depletion.

##### *Emerging uncertainties on future rate of recovery of the ozone layer present challenges for implementation of the Montreal Protocol and its amendments*

The time that it will take for a return of stratospheric ozone levels to historical values, the central goal of the Montreal Protocol and its amendments, is subject to a host of

uncertainties. These include unexpected emissions of controlled anthropogenic ozone-depleting substances (ODSs), slower-than-expected declines in atmospheric CCl<sub>4</sub>, possible increases in natural ODSs due to climate change, greenhouse gas increases, and stratospheric geoengineering. In one example, Stanley *et al.* (2020) found that global emissions of HFC-23, a by-product of HCFC-22 production, were greater in 2018 than at any previous year, whereas measures under the Kigali Amendment to the Montreal Protocol should have yielded a global emissions drop of 87% between 2014 and 2017. Finally, there are uncertainties in the emissions of uncontrolled short-lived ODSs that have been observed increasing in the atmosphere since 2017. As Fang *et al.* (2019) argue, these could delay the recovery of stratospheric ozone by up to decades. It is thus critical to ensure that the Montreal Protocol and its amendments be implemented effectively. This action should be supported by expansion of geographic coverage of atmospheric observations of ODSs, enhancement of source attribution modeling and improved understanding of the interactions between climate change and ozone recovery.

*Stratospheric Injection of Massive Smoke Plume from Canadian Boreal Fires in 2017 as Seen by DSCOVR-EPIC, CALIOP, and OMPS-LP Observations*

The 2017 wildfire season in western North America was unusually intense. Media outlets reported over 1,300 fires and more than 1.2 million hectares burned between April and November in the Canadian British Columbia province. In mid-August, the combination of very intense boreal fires and typical summer meteorological conditions led to the rapid formation fire-triggered convective clouds of considerable vertical extent. Because of the pyro-convective activity of these clouds, thousands of tons of carbon-containing smoke particles, also known as aerosols, were injected above 10 km in a few hours, some of which may have been directly injected in the stratosphere. Heating due to absorption of solar radiation induced lofting of the smoke plume into the stratosphere (generally above 12 km in this area), a region of the atmosphere where aerosol removal processes are slow. Because of their long residence time, stratospheric aerosols are very important as they affect Earth's radiative budget and climate. Torres *et al.* (2020) used satellite observations and models to describe the extended three-dimensional spatial distribution and long lifetime of the resulting aerosol plume that made this an unusual aerosol event.

In another paper, Yu *et al.* (2019) examined measurements from SAGE III/ISS and CALIPSO. They found that comparisons of model simulations to the rate of observed lofting indicated that 2% of the smoke mass was black carbon. The observed smoke lifetime in the stratosphere was 40% shorter than calculated with a standard model that does not consider photochemical loss of organic carbon. The observed rapid plume rise, latitudinal spread, and photochemical reactions provide new insights into potential global climate impacts from nuclear war.

*Trends and Variability in Stratospheric NO<sub>x</sub> Derived from Merged SAGE II and OSIRIS Satellite Observations*

Nitrogen oxides (NO<sub>x</sub>) in the stratosphere are produced from N<sub>2</sub>O, the dominant emission contributing to stratospheric ozone depletion in the 21st century and an important

anthropogenic greenhouse gas. Decades worth of observations are required in order to quantify the variability and trends in stratospheric NO<sub>x</sub> so that we can better understand their impact on climate. Dube *et al.* (2020) used the Stratospheric Aerosol and Gas Experiment (SAGE) II, a solar occultation instrument that measured NO<sub>2</sub> from 1984 to 2005, and the Optical Spectrograph and InfraRed Imager System (OSIRIS), a limb-scattering instrument that began measuring NO<sub>2</sub> in 2001. Taking advantage of the 4-year overlap between these instruments they were able to create a merged dataset of stratospheric NO<sub>2</sub>, spanning over 34 years, using a photochemical correction to account for the different times of day at which the instruments measure and to convert the NO<sub>2</sub> to NO<sub>x</sub>. A linear regression model was applied to the merged, deseasonalized data set to identify variability associated with long-term trends, the quasi-biennial oscillation (QBO), and volcanic aerosols. They found that high levels of aerosol associated with large volcanic eruptions greatly influenced the calculated long-term trend; when volcanic periods are excluded, the trend in NO<sub>x</sub> is ~10% per decade in the tropical lower stratosphere. In this case, the observed trends and variability from the satellite measurements show overall good agreement with simulations from the whole atmosphere community climate model (WACCM).

#### *Diagnosing Observed Stratospheric Water Vapor Relationships to the Cold Point Tropical Tropopause*

The humidity of the stratosphere is an important climate variable that accounts for as much as 30% of equilibrium climate sensitivity. While the dominant process controlling stratospheric humidity is the freeze drying that air experiences as it crosses the tropical tropopause, the degree to which moistening of the lower stratosphere by overshooting convection contributes to the global budget of stratospheric water remains uncertain. Randel and Park (2019) used the long-term record of stratospheric water vapor from NASA's Microwave Limb Sounder (MLS) to quantify the relationship between variability in stratospheric humidity and tropical tropopause temperature, confirming the dominant role of freeze drying. They showed no significant contributions to stratospheric humidity variability from overshooting convection on the ~15-year timescale considered. In contrast, Wang *et al.* (2019), while again confirming the centrality of freeze drying, showed that model predictions of the spatial patterns in stratospheric humidity show better agreement with the MLS record if those models include convective overshooting.

#### *Erythemal Radiation, Column Ozone and the North American Monsoon*

A recent study quantified the impact of summertime convection over North America on column ozone abundances and thus surface ultraviolet. Using observations from the Microwave Limb Sounder (MLS) and Ozone Monitoring Instrument (OMI) sensors on NASA's Aura satellite, Schoeberl *et al.* (2020) showed a ~0.8-0.9 spatial correlation between the patterns of enhancements in lower stratospheric water vapor (indicative of convection) and column ozone and surface UV. This correlation appears to be due to the elevation of the monsoonal tropopause and associated monsoonal convection. The increase in tropopause altitude reduces ozone column and increases surface UV. The study found no evidence of substantial heterogeneous chemical loss in lower

stratospheric ozone coincident with the stratospheric monsoonal water vapor enhancement, in contrast with proposed hypotheses postulating such a link.

*Reformulating the bromine alpha factor and equivalent effective stratospheric chlorine (EESC): evolution of ozone destruction rates of bromine and chlorine in future climate scenarios*

Future trajectories of the stratospheric trace gas background will alter the rates of bromine- and chlorine-mediated catalytic ozone destruction via changes in the partitioning of inorganic halogen reservoirs and the underlying temperature structure of the stratosphere. The current formulation of the bromine alpha factor, the ozone destroying power of stratospheric bromine atoms relative to stratospheric chlorine atoms, is invariant with the climate state. Klobas *et al.* (2020) reformulated the bromine alpha factor, introducing normalization to a benchmark chemistry–climate state and calculate an Equivalent Effective Stratospheric Benchmark normalized Chlorine (EESBnC) to reflect changes in the rates of both bromine- and chlorine-mediated ozone loss catalysis with time. They showed the ozone-processing power of the extrapolar stratosphere is significantly perturbed by future climate assumptions. Furthermore, their EESBnC-based estimate of the extrapolar ozone recovery date was shown to be in closer agreement with extrapolar ozone recovery dates predicted using more sophisticated 3-D chemistry–climate models than predictions made using equivalent effective stratospheric chlorine (EESC).

***E. Airborne and surface-based activities***

*North Atlantic Aerosols and Marine Ecosystems Study (NAAMES)*

NAAMES is the first EV-S mission focused on studying the coupling of the ocean ecosystem and atmosphere. Sea spray aerosol (SSA) consists of both sea salt and organic components. These aerosols affect Earth's climate by scattering solar radiation and by altering cloud properties. Bates *et al.* (2020) presented observations of SSA particles generated at sea using an over-the-side bubbling system (Sea Sweep) and an onboard plunging wave mesocosm (Marine Aerosol Reference Tank—MART) during five NAAMES cruises in the North Atlantic. These were timed to sample different stages of the North Atlantic plankton bloom and included transects from the oligotrophic Sargasso Sea to the biologically productive western subarctic. Their results show that the North Atlantic plankton bloom has little effect on the emission flux, organic fraction, or cloud condensation nuclei (CCN) activity of SSA, and therefore, plankton ecosystems do not need to be included in modeling aerosol indirect effects of primary SSA in global climate models or in chemical transport models.

*Investigation of factors controlling PM<sub>2.5</sub> variability across the South Korean Peninsula during KORUS-AQ*

The Korea-United States Air Quality Study (KORUS-AQ; May – June 2016) deployed instrumented aircraft and ground-based measurements to elucidate causes of poor air

quality related to high ozone and aerosol concentrations in South Korea. Jordan et al. (2020) evaluated data pertaining to aerosols (specifically, particulate matter with aerodynamic diameters  $<2.5 \mu\text{g}$ , PM<sub>2.5</sub>) and conditions leading to violations of South Korean air quality standards (24-hr mean PM<sub>2.5</sub>  $< 35 \mu\text{g m}^{-3}$ ). PM<sub>2.5</sub> variability from Air Korea monitors across South Korea. Detailed data from the Seoul vicinity were used to interpret factors that contribute to elevated PM<sub>2.5</sub>. They probed two meteorological periods drivers of elevated PM<sub>2.5</sub> and found that clear, dry conditions, with limited transport, promoted photochemical production of secondary organic aerosol from locally emitted precursors. In contrast, cloudy humid conditions fostered rapid heterogeneous secondary inorganic aerosol production from local and transported emissions. This was likely driven by a positive feedback mechanism where water uptake by aerosols increased through gas-to-particle partitioning. The cloudy conditions also reduced solar insolation, suppressing mixing and thus exacerbating PM<sub>2.5</sub> accumulation in a shallow boundary layer. The combination of factors contributing to enhanced PM<sub>2.5</sub> is challenging to model, complicating quantification of contributions to PM<sub>2.5</sub> from local versus upwind precursors and production. They recommend co-locating additional continuous measurements at a few AirKorea sites across South Korea to help resolve this and other outstanding questions: carbon monoxide/carbon dioxide (transboundary transport tracer), boundary layer height (surface PM<sub>2.5</sub> mixing depth), and aerosol composition with aerosol liquid water (meteorologically-dependent secondary production). They concluded that these data would aid future research to refine emissions targets to further improve South Korean PM<sub>2.5</sub> air quality.

*Observation-based modeling of ozone chemistry in the Seoul metropolitan area during the Korea-United States Air Quality Study (KORUS-AQ)*

The Seoul Metropolitan Area (SMA) has a population of 24 million and frequently experiences unhealthy levels of ozone (O<sub>3</sub>). Schroeder *et al.* (2020) used KORUS-AQ measurements to explore regional gradients in O<sub>3</sub> and its chemical precursors and used an observationally-constrained photochemical box model to quantify key aspects of O<sub>3</sub> production, including its sensitivity to precursor gases. They evaluated the box model's performance by comparing modeled concentrations of select secondary species to airborne measurements. These comparisons indicated that the steady-state assumption used in box models cannot describe select intermediate species, highlighting the importance of having a broad suite of trace gases as model constraints. When fully constrained, aggregated statistics of modeled O<sub>3</sub> production rates agreed with observed changes in O<sub>3</sub>, indicating that the box model was able to represent the majority of O<sub>3</sub> chemistry.

Comparison of airborne observations between urban Seoul and a downward receptor site reveal a positive gradient in O<sub>3</sub> coinciding with a negative gradient in NO<sub>x</sub>, no gradient in CH<sub>2</sub>O, and a slight positive gradient in modeled rates of O<sub>3</sub> production. Together, these observations indicate a radical-limited (VOC-limited) O<sub>3</sub> production environment in the SMA. Zero-out simulations identified C<sub>7+</sub> aromatics as the dominant VOC contributors to O<sub>3</sub> production, with isoprene and anthropogenic alkenes making smaller but appreciable contributions. Simulations of model sensitivity to decreases in NO<sub>x</sub> produced results that

were not spatially uniform, with large increases in O<sub>3</sub> production predicted for urban Seoul and decreases in O<sub>3</sub> production predicted for far-outlying areas. The policy implications of this work are clear: Effective O<sub>3</sub> mitigation strategies in the SMA must focus on reducing local emissions of C<sub>7+</sub> aromatics, while reductions in NO<sub>x</sub> emissions may increase O<sub>3</sub> in some areas but generally decrease the regional extent of O<sub>3</sub> exposure.

### **Section 1.1.9.2 Carbon Cycle and Ecosystems Focus Area**

Contributions from the Carbon Cycle and Ecosystems Focus area to Annual Performance Indicator 1.1.9 included scaling *in situ* processes with remote sensing in the Alaskan Arctic for carbon cycle analyses, northern Great Plains in the US for improved seasonal land cover change detection, as well as global ecosystem demography and biodiversity models. Socio-political drivers contributing to understanding land cover changes in eastern Europe and Asia are also highlighted.

#### ***Ocean Biology and Biogeochemistry***

The biological carbon pump (BCP) is responsible for sequestering roughly 5-10 Pg of carbon per year. Small changes in the BCP can significantly alter the ocean's capacity to sequester carbon; this in turn impacts atmospheric CO<sub>2</sub> and climate. Improving representation of the BCP's functioning in Earth system models is essential to reduce uncertainties in climate predictions. Buesseler et al. (2020) demonstrated that the varying depth of light penetration exerts a control on sinking organic carbon, and this varies by location and season. The authors make the case for improved ways to estimate BCP efficiency, which will lead to a better understanding of the mechanisms that control ocean carbon fluxes and its feedbacks on climate. Because of the significant importance of the BCP in carbon sequestration, it is important to understand the various mechanisms that control particulate organic carbon (POC) export out of the surface ocean, and what the relative importance of each is. Bisson et al. (2020) used a satellite-based mechanistic model of POC export to examine whether a variety of processes, such as size-specific physical aggregation, zooplankton fecal pellet production, and phytoplankton mortality, can improve the model's output and whether it can assess the role of each process in controlling global POC export. They concluded that zooplankton fecal fluxes are important for improving model output, but that field measurements of bulk ecosystem rates are needed to better constrain mechanistic models of global POC export.

#### ***Terrestrial Ecology***

##### ***Vulnerability and Resilience of Ecosystems***

Methane (CH<sub>4</sub>) emissions from thawing permafrost also amplify a climate warming feedbacks. However, upscaling of site-level CH<sub>4</sub> observations across diverse Arctic landscapes remains highly uncertain, compromising accuracy of current pan-Arctic CH<sub>4</sub> budgets and confidence in model forecasts. Recent studies have demonstrated the potential of using measurements from airborne and satellite remote sensing data to scale ground based CH<sub>4</sub> inventories. For example, Elder et al. (2020) used data from NASA's Airborne Visible Infrared Imaging Spectroradiometer to successfully detect CH<sub>4</sub> emission hotspots associated with thermokarst lakes across a 30,000 km<sup>2</sup> permafrost landscape. In another study, Engram et al. (2020) used spaceborne synthetic aperture radar data to image ebullition bubbles (which are filled with CH<sub>4</sub>) in frozen lakes, ultimately creating ebullition-flux maps for 5,143 Alaskan lakes. Seasonal studies in the Amazon corroborate those of the northern latitudes using lidar data and an Ecosystem Demography model. Longo et al. (2020) found that carbon fluxes and fire vulnerability across degraded and intact forests were comparable in normal years, whereas drought

years showed significant sources of carbon as well as enhanced fire vulnerability in degraded forests.

## **Land Cover/Land Use Change**

### *U.S. Northern Great Plains*

Developing seasonal phenological land cover maps has been generally constrained by timing and resolution of available remote sensing data. Nguyen et al., (2020) demonstrated an approach to map land cover utilizing multi-temporal Earth Observation data from Landsat and MODIS. They first built an annual time series of accumulated growing degree-days (AGDD) from MODIS 8-day composites of land surface temperatures. Using the Enhanced Vegetation Index (EVI) annual image time series through land surface phenology modeling, land cover/land use (LCLU) classification can embrace both seasonality and interannual variability, thereby increasing the accuracy of LCLU change detection.

### *Ukraine*

Skakun et al., (2019) reported that net cropland losses were not uniform across the regions, and were more substantial in the areas not under control of the Ukrainian Government (22% of net cropland area loss compared to cropland areas in 2013) and within a buffer zone along the conflict border line (46%), where combat activities occur. These results highlight the impact of the conflict on agriculture and the utility of spatially explicit information acquired from Earth observation satellites, especially for areas, where collecting ground-based data is impractical.

### *South/Southeast Asia*

A special issue on land-cover and land-use change in South/Southeast Asia (Vadrevu et al. 2019) provides results in five different articles on: 1) mangrove mapping in Indonesia highlighting the use of novel vegetation indices for achieving 92% accuracy; 2) the use of multiple-class neural networks for urban pattern characterization yielding over 87% accuracy in Hanoi, Vietnam; 3) cropland mapping in India with integrated RADARSAT active remote sensing data and support vector machines, and reporting 92.7% overall classification accuracy; 4) the use of the Cellular Automata Markov Chain model for predictive LCLUC modeling in Indonesia; and 5) the impacts of land-cover changes on the environment in Margalla Hills, Pakistan with an up to 3 degree C increase in the surface temperature due to forests-to-soil and water-to-agriculture conversion from 1992-2000.

Results from Zhang et al., (2020) show strong spatial consistencies between rice paddy area and atmospheric methane concentration  $XCH_4$  and seasonal consistencies between rice plant growth and  $XCH_4$ . Results also indicate decreasing trend in rice paddy area in monsoon Asia since 2007, which suggests that the change in rice paddy area could not be one of the major drivers for the renewed  $XCH_4$  growth, thus other sources and sinks should be further investigated. Findings highlight the importance of satellite-based paddy rice datasets in understanding the spatial-temporal dynamics of  $XCH_4$  in monsoon Asia.

### *Central Asia*

In a compilation book titled “Landscape Dynamics of Drylands Across Greater Central Asia: People, Societies and Ecosystems” Gutman et al., (2020) describe and analyze various patterns, processes, and consequences to the population and landscapes of the Greater Central Asia region as a result of the breakup of the Soviet Union, which had huge impacts on the structure of the society, local and region. It is a compilation of results from studies on land-cover and land-use changes and their interactions with carbon, water and energy cycles, landscape dynamics, the role of institutional changes, as well as the consequences of global changes. Those changes included transitioning to privately owned fields and enterprises, with some arable lands abandoned, while some idled, or continued with cultivation. The book is a truly interdisciplinary collaborative effort by an international team consisting of scholars from the USA, Europe, Central Asia, and elsewhere, under the auspices of the Northern Eurasia Earth Science Partnership Initiative (NEESPI) supported primarily by the NASA Land-Cover/Land-Use Change Program. It is of interest and directed to a broad range of scientists within natural and social sciences, those involved in studying recent and ongoing changes in drylands, be they senior scientists, early career scientists, or students. These studies provide analysis of the dramatic changes in land uses triggered by an abrupt change in economies of the region and land management. Lessons learned from these studies are additional evidences for the sustainability development of drylands. The satellite data used for these studies were mostly from NASA and ESA optical sensors with coarse (~5 km to 250 m) and medium (100 m to 10 m) spatial resolutions.

### ***Biodiversity***

#### *Developing Observation Tools for Making Ecological Forecasts*

Ecological models play a key role in supporting conservation, restoration, and sustainable development. Advances in modelling, analytics, and artificial intelligence have led to major innovation in the ability to detect biological phenomena. For instance, the use of remote sensing for species distribution modeling has enabled the development of ‘essential biodiversity variables’ (EBVs) for a unified global capture of species populations in space and time (Jetz et al. 2019). Mechanistic climate reconstructions models have enabled simulation of 50,000 years of bird migration worldwide, highlighting the strong flexibility of the global bird migration system and offering a baseline in the context of on-going anthropogenic climate change (Somville et al. 2020). Artificial intelligence and cloud computing resources expand the utility of remote sensing tools for decision making. For instance, Sousa et al. (2020) generated ecosystem maps for Liberia and Gabon using a random forest pixel-based classification system which improves the accuracy of prior products for this region. This simple and highly replicable approach supports the implementation of international agreements to incorporate the value of nature into national planning.

### **Section 1.1.9.3 Climate Variability and Change Focus Area**

Highlights of results published this past year related to the enhancement of the systems-level understanding and prediction of the Earth system relevant to the CVC FA are summarized below:

#### **Sea Ice in the Climate System**

Leads (narrow cracks) are a key feature of the Arctic ice pack during the winter, owing to their substantial contribution to the surface energy balance. According to the present understanding, enhanced heat and moisture fluxes from high lead concentrations tend to produce more boundary layer clouds. Using surface- and satellite-based observations, Li et al. (2020) found that abundant boundary layer clouds are associated with low lead incidence periods, while fewer boundary layer clouds are observed for high lead incidence periods. Motivated by these counterintuitive results, they conducted three-dimensional cloud-resolving simulations to investigate the underlying physics. They find that newly frozen leads with large sensible heat flux but low latent heat flux tend to dissipate low clouds. This finding indicates that the observed high lead fractions likely consist mostly of newly frozen leads that reduce any pre-existing low-level cloudiness, which in turn decreases downwelling infrared flux and accelerates the freezing of sea ice.

Webster et al. (2019) analyzed the role of cyclone activity on the seasonal buildup of snow on Arctic sea ice using model, satellite, and in situ data over 1979–2016. On average, 44% of the variability in monthly snow accumulation was controlled by cyclone snowfall and 29% by sea-ice freeze-up. However, there were strong spatio-temporal differences. Cyclone snowfall comprised ~50% of total snowfall in the Pacific compared to 83% in the Atlantic. While cyclones are stronger in the Atlantic, Pacific snow accumulation is more sensitive to cyclone strength. Identifying the mechanisms controlling the timing and magnitude of snow accumulation on sea ice is crucial for understanding snow's net effect on the surface energy budget and sea-ice mass balance.

The release of Br<sub>2</sub> from the surface snowpack following polar sunrise leads to boundary layer ozone depletion events as well as mercury deposition events. Due to the coupling between the atmosphere and the cryosphere, the changing Arctic sea ice conditions are expected to impact the production of molecular halogens from the snowpack. While the snowpack in sea ice regions controls the oxidative capacity of the Arctic atmosphere, measurements of snowpack halide concentrations remain sparse, particularly in the high Arctic, limiting our understanding of and ability to parameterize snowpack participation in tropospheric halogen chemistry. To address this gap, Peterson et al. (2019) measured concentrations of chloride, bromide, and sodium in snow samples collected during polar spring above remote multi-year sea ice (MYI) and first-year sea ice (FYI) north of Greenland and Alaska, as well as in the central Arctic, and compared these measurements to a larger dataset collected in the Alaskan coastal Arctic. Regardless of sea ice region, these surface snow samples generally featured lower salinities compared to coastal snow.

Surface snow in FYI regions was typically enriched in bromide and chloride compared to seawater, indicating snowpack deposition of bromine and chlorine-containing trace gases and an ability of the snowpack to participate further in bromine and chlorine activation processes. In contrast, surface snow in MYI regions was more often depleted in bromide, indicating it served as a source of bromine-containing trace gases to the atmosphere prior to sampling. Measurements at various snow depths indicate that the deposition of sea salt aerosols and halogen-containing trace gases to the snowpack surface played a larger role in determining surface snow halide concentrations compared to upward brine migration from sea ice. Calculated enrichment factors for bromide and chloride, relative to sodium, in the MYI snow samples suggest that MYI regions, in addition to FYI regions, have the potential to play an active role in Arctic boundary layer bromine and chlorine chemistry. The ability of MYI regions to participate in springtime atmospheric halogen chemistry should be considered in regional modeling of halogen activation and interpretation of satellite-based tropospheric bromine monoxide column measurements.

A biophysical model (Zhang et al., 2019) shows that Beaufort Gyre intensification in 2004–2016 was followed by relaxation in 2017–2018, based on a Beaufort Gyre variability index. Beaufort Gyre intensification leads to enhanced downwelling in the central Canada Basin and upwelling along the coast. In the central Canada Basin, enhanced downwelling reduces nutrients, thus lowering primary productivity and plankton biomass. Enhanced upwelling along the coast and in parts of the Chukchi shelf/slope increases nutrients, leading to elevated primary productivity/biomass in the Pacific Arctic Ocean outside of the central Canada Basin. The overall Pacific Arctic Ocean primary productivity/biomass was dominated by the shelf/slope response and thus increases during Beaufort Gyre intensification. As the Beaufort Gyre relaxes in 2017–2018, these processes largely reversed, with increasing primary productivity/biomass in the central Canada Basin and decreasing primary productivity/biomass in most of the shelf/slope regions. Because the shelf/slope regions are much more productive than the central Canada Basin, Beaufort Gyre relaxation has the tendency to reduce the overall production in the Pacific Arctic Ocean.

In the Antarctic Amundsen Sea, modified Circumpolar Deep Water (mCDW) intrudes into ice shelf cavities, causing high ice shelf melting near the ice sheet grounding lines, accelerating ice flow, and controlling the pace of future Antarctic contributions to global sea level. The pathways of mCDW towards grounding lines are crucial as they directly control the heat reaching the ice. A realistic representation of mCDW circulation, however, remains challenging due to the sparsity of *in-situ* observations and the difficulty of ocean models to reproduce the available observations. Nakayama et al. (2019) use an unprecedentedly high-resolution (200 m horizontal and 10 m vertical grid spacing) ocean model that resolves shelf-sea and sub-ice-shelf environments in qualitative agreement with existing observations during austral summer conditions. They demonstrate that the waters reaching the Pine Island and Thwaites grounding lines follow specific, topographically-constrained routes, all passing through a relatively small area located around 104°W and 74.3°S. The temporal and spatial variabilities of ice shelf melt rates are dominantly controlled by the sub-ice shelf ocean current. Their findings highlight the

importance of accurate and high-resolution ocean bathymetry and subglacial topography for determining mCDW pathways and ice shelf melt rates.

All exchanges between the open ocean and the Antarctic continental shelf must cross the Antarctic Slope Current (ASC). Previous studies indicate that these exchanges are strongly influenced by mesoscale and tidal variability, yet the mechanisms responsible for setting the ASC's transport and structure have received relatively little attention. Steward et al. (2019) investigated the roles of winds, eddies, and tides in accelerating the ASC using a global ocean–sea ice simulation with very high resolution ( $1/48^\circ$  grid spacing). They found that the circulation along the continental slope is accelerated both by surface stresses, ultimately sourced from the easterly winds, and by mesoscale eddy vorticity fluxes. At the continental shelf break, the ASC exhibits a narrow ( $\sim 30\text{--}50$  km), swift ( $>0.2$  m s $^{-1}$ ) jet, consistent with in situ observations. In this jet the surface stress is substantially reduced, and may even vanish or be directed eastward, because the ocean surface speed matches or exceeds that of the sea ice. The shelf break jet is shown to be accelerated by tidal momentum advection, consistent with the phenomenon of tidal rectification. Consequently, the shoreward Ekman transport vanishes and thus the mean overturning circulation that steepens the Antarctic Slope Front (ASF) is primarily due to tidal acceleration. These findings imply that the circulation and mean overturning of the ASC are not only determined by near-Antarctic winds, but also depend crucially on sea ice cover, regionally-dependent mesoscale eddy activity over the continental slope, and the amplitude of tidal flows across the continental shelf break.

### **Land Ice in the Climate System**

The speed of Greenland's fastest glacier, Jakobshavn Isbræ, has varied substantially since its speed-up in the late 1990s. Joughin et al. (2020) presented observations of surface velocity, mélange rigidity, and surface elevation to examine its behavior over the last decade. Consistent with earlier results, they find a pronounced cycle of summer speed-up and thinning followed by winter slowdown and thickening. There were extended periods of rigid mélange in the winters of 2016–2017 and 2017–2018, concurrent with terminus advances  $\sim 6$  km farther than in the several winters prior. These terminus advances to shallower depths caused slowdowns, leading to substantial thickening, as has been noted elsewhere. The extended periods of rigid mélange coincide well with a period of cooler waters in Disko Bay. Thus, along with the relative timing of the seasonal slowdown, their results suggest that the ocean's dominant influence on Jakobshavn Isbræ is through its effect on winter mélange rigidity, rather than summer submarine melting. The elevation time series also reveals that in summers when the area upstream of the terminus approaches flotation, large surface depressions can form, which eventually become the detachment points for major calving events. It appears that as elevations approach flotation, basal crevasses can form, which initiates a necking process that forms the depressions. The elevation data also show that steep cliffs often evolve into short floating extensions, rather than collapsing catastrophically due to brittle failure.

Maps of the landscape formed by past ice sheets are our best tool for reconstructing historic ice sheet behavior. But models of glacier erosion and deposition that explain

mapped features are relatively untested, and without observations of landforms developing *in situ*, postglacial landscapes can provide only qualitative insight into past ice sheet conditions. Holschuh et al. (2019) present the first swath radar data collected in Antarctica, demonstrating the ability of swath radar technology to map the subglacial environment of Thwaites Glacier (West Antarctica) at comparable resolutions to digital elevation models of deglaciated terrain. Incompatibility between measured bedform orientation and predicted subglacial water pathways indicates that ice, not water, is the primary actor in initiating bedform development at Thwaites Glacier. These data show no clear relationship between morphology and glacier speed, a weak relationship between morphology and basal shear stress, and highlight a likely role for preexisting geology in glacial bedform shape.

Between 1992 and 2017, the Antarctic Ice Sheet (AIS) lost ice equivalent to  $7.6 \pm 3.9$  mm of sea level rise. AIS mass loss is mitigated by ice shelves that provide a buttress by regulating ice flow from tributary glaciers. However, ice-shelf stability is threatened by meltwater ponding, which may initiate, or reactivate preexisting, fractures, currently poorly understood processes. Through ground penetrating radar (GPR) analysis over a buried lake in the grounding zone of an East Antarctic ice shelf, Dumire et al. (2020) presented the first field observations of a lake drainage event in Antarctica via vertical fractures. Concurrent with the lake drainage event, they observe a decrease in surface elevation and an increase in Sentinel-1 backscatter. They suggest that fractures that are initiated or reactivated by lake drainage events in a grounding zone will propagate with ice flow onto the ice shelf itself, where they may have implications for its stability.

Ocean-driven basal melting of Antarctica's floating ice shelves accounts for about half of their mass loss in steady state, where gains in ice-shelf mass are balanced by losses. Although this melting does not contribute directly to sea level, these ice shelves help regulate the flow of grounded ice to the ocean. Consequently, ice shelf thinning due to melt indirectly contributes to sea level rise. Adusumilli et al. (2020) combined surface height data from satellite radar altimeters with satellite-derived ice velocities and a new model of firn-layer evolution to generate a high-resolution map of time-averaged (2010–2018) basal melt rates and time series (1994–2018) of meltwater fluxes for most ice shelves. Ice-shelf thickness changes driven by varying basal melt rates modulate mass loss from the grounded ice sheet and its contribution to sea level, and the changing meltwater fluxes influence climate processes in the Southern Ocean. Existing continent-wide melt-rate datasets have no temporal variability, introducing uncertainties in sea level and climate projections. For the four largest 'cold-water' ice shelves, they partition meltwater fluxes into deep and shallow sources to reveal distinct signatures of temporal variability, providing insights into climate forcing of basal melting and the impact of this melting on the Southern Ocean.

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### **Oceans in the Climate System: Modeling and Prediction**

One of the scientific thrusts of the Physical Oceanography program and CVC focus area is improving our understanding and prediction of the large-scale ocean energy, heat, and water cycle budgets on time scales of seasons to decades by combining ocean observations within a theoretical framework. With certain similarities to numerical

weather forecasting, there are subtle but important considerations in ocean state estimation, namely conservation of basic physical properties such as heat, salt, or momentum, that require alternative data assimilation approaches. While budget closure is of little importance for weather forecasts, as their violation has no impact on short-range prediction skill, budget closure and thus absence of discontinuity in the analysis time when the model is forced toward the data is crucial to the understanding of climate change and ocean's role in climate. NASA supports production of a robust estimate and evolution of ocean state over the past few decades through development of the Estimating the Circulation and Climate of the Ocean (ECCO) framework (Fukumori et al., 2020). The framework integrates nearly all existing ocean observations under the constraints of the conservation laws of physics and provides a description of the ocean circulation over the past two decades, as well as the evolution of sea ice and changes in the ocean biogeochemistry. Today, ECCO supports a wide range of applications in climate research, including ocean heat content variability, sea level rise, air-sea interaction, and global ocean circulation, including ocean-ice coupling (see <https://ecco-group.org/> for full list of recent publications).

The ECCO approach uses the same mathematical underpinnings as modern machine learning (ML) methods, e.g., iterative gradient descent until the errors are reduced, and thus invites natural cross-pollination between the ECCO geophysical and data science communities. A new study by Sonnewald et al. (2019) applied a machine learning, K-means clustering algorithm that filtered through a vast quantity of data to identify patterns in the ocean that have similar physics. The results show that there are five clusters that compose 93.7% of the global ocean, consistent with the canonical regimes, such as those driven by the balance between the wind pressure on the surface of the ocean and the bottom torques. This consistency allowed Sonnewald et al. (2019) to guide and test the machine learning algorithm using classical ocean physics principles, building a helpful bridge between machine learning and oceanography.

In addition to modeling and state estimation, another related issue that is gaining momentum is ocean predictability and prediction. Buckley et al. (2019) examined the extent to which sea surface temperatures in the Atlantic Ocean can be predictable – an important question due to the strong climate impacts of ocean temperatures on the Atlantic hurricanes, as well as weather and precipitation patterns over continental US and Europe. Unlike the majority of the predictability studies that are based on models, Buckley et al. (2019) use a purely observational approach and estimate a lower bound on predictability time scales for sea surface temperature and upper-ocean heat content in the North Atlantic. They found that predictability for decadal variations in sea surface temperature is generally 3 to 4 years over most of the North Atlantic domain, with predictability generally being larger and reaching 4 to 6 years in subpolar regions. Their central hypothesis is that predictability time scales can be explained by spatial variations in the ocean mixed layer depth, and longer time scales of predictability of the North Atlantic are explained by its deeper (relative to other ocean basins) wintertime mixed layer depth.

Prediction of tides and tidally-forced motions is one of longest application of dynamical theory, dating back to early work by Laplace (1775) of what is now known as the shallow-water equations to modern classes of models that predict ocean response to tidal and atmospheric forcing that resolve a rich spectrum of tides and internal gravity waves (see, e.g., Arbic et al. (2018) for review). In particular, prediction of tides of amplified magnitudes, or high tides, has gained renewed interest due to their linkage to the increased occurrence and severity of local flood events in coastal areas around the United States. The increase in high-tide flooding has been attributed to both global warming tendencies and sea level rise, as well as inter-annual and decadal climate and ocean fluctuations. Thompson et al. (2019) develop a probabilistic projection model, which formed the bases of the NASA Flooding Days tool (now available at <https://sealevel.nasa.gov>) to allow decision makers to assess how sea level rise and other factors will affect the frequency of high-tide flooding in coming decades on a location-specific basis. The projections are based on an analysis of astronomical tides and other natural fluctuations in tide gauge data in combination with sea level rise projections based on climate models and climate assessments. The tool is designed to be flexible and adapt to the user's needs by allowing for results to be viewed for multiple sea level rise projections across a range of flooding thresholds.

### **Earth System Modeling**

Results from studies utilizing CVC-supported Earth system models aimed at improving the understanding of the interacting Earth system and Earth system prediction included:

#### ***Climate modeling advances***

ESMs include a large number of processes and feedbacks and some climate-relevant processes still have fairly high uncertainties. Heinze et al. (2019) present an overview of climate feedbacks for Earth system components currently included in state-of-the-art ESMs and discuss the challenges to evaluate and quantify them. Uncertainties in feedback quantification arise from the interdependencies of biogeochemical matter fluxes and physical properties, the spatial and temporal heterogeneity of processes, and the lack of long-term continuous observational data to constrain them. The study presents an outlook for promising approaches that can help to quantify and to constrain the large number of feedbacks in ESMs in the future, and updates and significantly expands upon the last comprehensive overview of climate feedbacks in ESMs, which was produced 15 years ago.

Correcting errors in climate models is difficult due to their interactivity. Modifications to improve one variable often degrade others for instance. Schubert et al. (2019) outline a framework for identifying the geographical sources of biases in climate models, using the Modern-Era Retrospective Analysis for Research and Applications (MERRA)-2 reanalysis and the GEOS AGCM. By using tendency bias corrections (TBCs) to correct the model over well-defined regions, the paper shows how the reduced errors in these regions manifest themselves both locally and remotely through large-scale teleconnections. Companion experiments in which the model is fully corrected - that is,

constrained to remain close to an analysis at each time step - in the various regions provide an upper bound to the local and remote TBC impacts. The results highlight the ability of the approach to isolate the geographical sources of some of the long-standing boreal summer biases of the GEOS model, including a stunted North Pacific summer jet, a dry bias in the U.S. Great Plains, and a warm bias over most of the Northern Hemisphere land. In particular, the TBC over a region that encompasses Tibet has by far the largest impact (compared with all other regions) on the NH summer jets and related variables, leading to significant improvements in the simulation of North American temperature and, to a lesser degree, precipitation.

***Clouds and cloud process modeling advances:***

Understanding and proper representation of stratocumulus clouds in climate models is critical and a large source of divergence between climate models. Matheou and Teixeira (2019) conducted a series of numerical experiments to investigate the physics of a stratocumulus cloud and the performance of a large-eddy simulation (LES) model. The simulations show a delicate balance of physical processes with some sensitivities amplified by numerical model features. Even though cloud-top radiative cooling is regarded as a key attribute of stratocumulus, the simulations suggest that surface fluxes and surface shear significantly contribute to the total turbulent kinetic energy. Turbulence spectra exhibit inertial range scaling away from the confinement effects of the surface and inversion. This improved understanding of the multiple factors which control stratocumulus should lead to better representation in global climate models..

The MAP program within the CVC FA supports the widely used MERRA-2 global atmospheric reanalysis. Due to its popularity it is important to characterize its capabilities. Kim et al. (2020) examines MERRA-2 tropical cyclone (TC) statistics, focusing on the climatological-mean genesis regions, tracks and their lifetime maximum intensity, as well as the interannual and intraseasonal variations in TC activity. MERRA-2 represents the spatial distribution of the TC genesis location and the tracks realistically over all main development regions (MDRs), but the simulated TCs are initiated at lower latitudes closer to the equator compared with the observations. In spite of the discrepancies in the annual TC number, the seasonal variation of TC genesis is realistic in MERRA-2. MERRA-2 also captures the TC intensity relationship between the minimum pressure and the maximum surface wind speed at the mature stage, although the maximum intensity is weaker than in the observations. MERRA-2 also describes the changes in the TC genesis region and tracks realistically according to the different phases of El Nino and the Southern Oscillation (ENSO) and the Madden-Julian Oscillation (MJO), although it is less realistic over the North Indian Ocean.

***Land and land/atmosphere coupling advances***

Soil moisture can significantly affect the characteristics of weather events occurring over land. Nair et al. (2020) found that extreme flooding over southern Louisiana in mid-

August of 2016 resulted from an unusual tropical low that formed and intensified over land. Their conclusions were based on numerical experiments to highlight the role of soil moisture and wetlands, which has been named the 'Brown Ocean' effect, on the maintenance or intensification of quasi-tropical systems. Storm evolution in a control experiment with wet antecedent soils most resembled tropical lows that form and intensify over oceans. Developing agricultural croplands and restoring wetlands from open water can impede intensification of tropical systems that affect the area.

Vegetation plays a fundamental role not only in the energy and carbon cycles but also in the global water balance by controlling surface evapotranspiration (ET). Thus, accurately estimating vegetation-related variables has the potential to improve our understanding and estimation of the dynamic interactions between the water, energy, and carbon cycles. Zhang et al. (2020) assessed the extent to which a land surface model can be optimized through the assimilation of leaf area index (LAI) observations at the global scale. LAI data assimilation not only effectively reduced errors in LAI model simulations but also improved the modeled water flux and storage variables considered, even in extremely wet conditions. However, it did worsen some of the modeled water-related variables when the forcing precipitation was affected by a dry bias. This was due to the fact that the amount of water in the LSM is conservative. The LAI assimilation introduced more vegetation, which requires more water than what was available within the soil.

### *Cryospheric modeling advances*

Ice sheet numerical modeling is an important tool to estimate the dynamic contribution of the Antarctic ice sheet to sea level rise over the coming centuries. The influence of initial conditions on ice sheet model simulations, however, is still unclear. Seroussi et al. (2019) describe an initial state intercomparison exercise (initMIP) to compare, evaluate, and improve initialization procedures and estimate their impact on century-scale simulations. initMIP is the first set of experiments of the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6), the primary Coupled Model Intercomparison Project Phase 6 (CMIP6) activity focusing on the Greenland and Antarctic ice sheets. This study presents the results from 25 simulations performed by 16 international modeling groups. Good agreement exists among model responses to the surface mass balance anomaly but large variations in responses to the basal melting anomaly, due to differences in the extent of ice shelves and their upstream tributaries, the numerical treatment of grounding line, and the initial ocean conditions.

The evaporative source of the precipitation that falls over Greenland is still unclear, as well as the potential change with the climate, with previous studies limited in terms of season or transport time. Nussbaumer et al. (2019) used the CVC-supported NASA GISS model to determine the sources of moisture for Greenland precipitation. The study found that the North Atlantic is the largest source for every season except summer, when land-based moisture sources become larger. These sources vary over time, particularly in response to the Greenland Blocking climate index. In addition, the study found a long-term change in the moisture source for Northwest Greenland, with more water evaporating from locations closer to Greenland itself. This is partly due to the loss of sea

ice and warming sea surface temperatures close to Greenland, resulting in more local evaporation.

### *Chemistry/climate modeling advances*

The year 2020 has been the “Year of the Coronavirus,” and Earth system modeling efforts supported within the CVC focus area have addressed the issue. For instance, Liu et al. (2020) used the CVC-supported GEOS modeling system to find that China’s policy interventions to reduce the spread of the coronavirus disease-2019 had environmental and economic impacts. Tropospheric nitrogen dioxide is a proxy for economic activities, and satellite measurements show a 48% drop in tropospheric nitrogen dioxide vertical column densities from the 20 days averaged before the 2020 Lunar New Year to the 20 days averaged after. This reduction is related to two of the government’s actions: the announcement of the first Covid-19 report in each province and the date of a province’s lockdown. Both actions are associated with nearly the same magnitude of reductions.

### *Climate prediction advances*

Earth's global “climate sensitivity” is a fundamental quantitative measure of the susceptibility of Earth's climate to human influence. A landmark report in 1979 concluded that it probably lies between 1.5-4.5°C per doubling of atmospheric carbon dioxide, assuming that other influences on climate remain unchanged. In the 40 years since, it has appeared difficult to reduce this uncertainty range. Sherwood et al. (2020) assess all lines of evidence and find that a large volume of consistent evidence now points to a more confident view of a climate sensitivity near the middle or upper part of this range.

Understanding the response of atmospheric blocking events to climate change has been of great interest in recent years and is important to the representation and prediction of climate extremes. However, potential changes in the blocking area have not received as much attention. Using two large-ensemble, fully coupled general circulation model (GCM) simulations, Nabizadeh et al. (2019) showed that the size of blocking events increases with climate change, particularly in the Northern Hemisphere. They derive a scaling law for the size of blocking events, which shows that area mostly scales with width of the jet times the length of stationary Rossby waves, and validate the law in a range of idealized GCM simulations.

NASA ESD invests in research to advance prediction on timescales ranging from the weather timescale to multidecadal climate timescales. Ensemble forecasting, either from the single or multimodel perspectives, has been a critical advance at all of these timescales. At the subseasonal timescale, the Subseasonal Experiment (SubX) is designed around operational requirements and the seven global model ensemble members have produced 17 years of retrospective forecasts and more than a year of weekly real-time forecasts. SubX shows skill for temperature and precipitation 3 weeks ahead of time in specific regions, and the ensemble mean is more skillful than any individual model overall. SubX produces skillful predictions of the MJO 4 weeks in advance and of the

## Management and Performance: FY 2020 Annual Performance Report

NAO 2 weeks in advance, and provides information on the potential for extreme precipitation associated with tropical cyclones, which can help emergency management and aid organizations to plan for disasters.

NASA contributes results to the SubX ensemble from its subseasonal-to-seasonal (S2S) prediction system, the GEOS-S2S. Molod et al. (2020) describe a new version of the Goddard Earth Observing System (GEOS) Subseasonal to Seasonal prediction (S2S) system, GEOS-S2S-2, that represents a substantial improvement in performance and infrastructure over the previous system. In the new system the climate of the atmosphere and ocean shows a substantial reduction in bias, and an improved coupled reanalysis attributed to the assimilation of along-track absolute dynamic topography. A much improved prediction of the Madden-Julian Oscillation is produced, and on a seasonal scale the tropical Pacific forecasts show substantial improvement.

#### **Section 1.1.9.4 Earth Surface and Interior Focus Area**

NASA's Earth Surface and Interior focus area (ESI) supports research aimed at characterizing the dynamics of the solid Earth, improving the capability to assess and respond to natural hazards and extreme events. Building on the body of work under 1.1.8 "characterizing the behavior of the Earth system," ESI studies seek to improve understanding of the interacting processes that "control the behavior of the Earth system" and hence "improve predictive capability" as described under performance goal 1.1.9. Improving predictive capability in ESI centers on working towards probabilistic forecasting, since the prediction of place, time, and intensity of an event in the solid-Earth system is generally not yet possible. ESI predictive capabilities may also address other long-term transient processes such as ongoing vertical land motion associated with fluid injection or withdrawal, volcanic unrest, soil compaction, and other near- or subsurface processes. With this in mind, studies that inform, or develop capabilities to help inform the occurrence of future events or the effects they may have on a larger system are classified under 1.1.9.

### **Geohazards**

One of the strengths of ESI relates to analyzing and modeling datasets derived from various remote sensing techniques to forecast the likelihood of geohazards. The societal benefits of these findings are significant as they reduce the risk on the life and livelihood of people that may be affected by these hazards. This year, geohazard forecasting techniques have been employed to address three types of hazards: earthquakes, volcanoes, and landslides.

#### **Earthquakes**

Identifying the methods for monitoring and measuring earthquakes and the seismic cycle are useful in mitigating and forecasting future events. Donnellan et al., (IGARSS, 2019) presented a concept for the Quantify Uncertainty and Kinematics of Earth Systems (QUAKES) imager. QUAKES is a single platform with a combination of interferometry and optical imaging instruments that produces a uniform deformation field that can serve as a baseline for quantifying geodetic measurements of earthquakes as well as landslides, wildfire extent, volcanoes, and anthropogenic deformation. To better understand the seismic cycle, Gualandi et al., (*Earth Planet. Sci. Lett.*, 2020) examines how aftershocks are related to major earthquakes by identifying how after slip and viscoelastic deformation influence it. They found that these factors affect the occurrence rate and type of aftershock (e.g., clustered, non-clustered), as well as the range of time and distance one earthquake can influence viscoelastic relaxation on another fault

Scientists have tried to understand for decades how different natural forces pressing on Earth's surface might help explain changes in earthquake rates— fluctuations in hydrological loading cycles is one such stress. Carlson et al., (*J. Geophys. Res.*, 2020) demonstrate how hydrologic unloading measured by both GRACE and InSAR data in the Central Valley from the 2012-2015 drought and continuing due to pumping can modulate crustal stress resulting in a higher than average seismic moment (earthquake magnitude). Similar studies were performed by Johnson et al., (*Earth Planet. Sci. Lett.*, 2020) in southern Alaska and Xue et al., (*Geophys. Res. Lett.*, 2020) in the western branch of the

East African Rift. They found that shallow faults have a greater likelihood of being affected by hydrologic loading and that the rate of seismicity correlates with variations in loading.

Since the discovery of slow slip events (SSEs) more than two decades ago, it has been suggested that SSEs may trigger seismic events such as earthquakes and long-lived tremors. Advances in geodetic techniques have enabled the detection and improved the accuracy of SSEs, however, it has been difficult to investigate the physical mechanism linking SSEs to seismic events. Recent studies have demonstrated the complexities of the relationship between SSEs and earthquake processes. Tymofyeyeva et al., (*J. Geophys. Res.*, 2019) found evidence that a SSE on the San Andreas fault was triggered minutes after the 2017 Mw 8.2 Chiapas (Mexico) Earthquake, occurring 3000 km away using InSAR observations derived from Sentinel-1 data. Khoshmanesh et al., (*Earth Planet. Sci. Lett.*, 2020), identified a link between SSEs and the triggering of larger earthquakes from GPS measurements of the oceanic-crustal subducting plate boundary along the northeastern Japan megathrust compiled from 1996-2003. They determined that SSEs promote stress changes in the surrounding seismogenic zone that can cause a domino effect leading to the triggering of a major earthquake providing intriguing new insights into the relationship between SSEs and earthquake processes, advancing goals outlined under *CORE Report 1*. [Plate boundaries].

## **Volcanoes**

Understanding the processes that lead to an eruption help researchers to better forecast when the next volcanic eruption might occur. Some closed volcanic systems have deformation that can emerge or intensify weeks to months before a volcanic eruption. This year, several different studies have focused on how the deformation observations relating to the 2008 Okmok, AK eruption can be used to forecast future volcanic events. Albright et al., (*Geophys. Res. Lett.*, 2019) incorporated InSAR and GPS Okmok data into the Ensemble Kalman Filter (EnKF) to retrospectively identify precursory eruptive signals weeks before the 2008 eruption despite these signals being subtle on their own. Xue et al., (*Journal Geophys. Res.*, 2020) incorporated GPS and InSAR data to model the post-eruptive deformation from the same event and found a newly developed shallow sill at Okmok with regular intrusive episodes from 2008 to 2019 that occur in increasing regularity, indicating the need for continued monitoring of this volcano.

One area of future research identified in the *CORE Report* [4. Magmatic systems], states “the use of airborne and spaceborne spectral instruments to provide unique thermal and chemical information on active volcanoes.” Lundgren, et al. (*Scientific Reports*, 2020) combined thermal infrared (TIR) measurements and InSAR observation to identify ongoing uplift and the increase of thermal output surrounding the Duymo volcanic system in Argentina. This study identifies increasing volcanic activity at the system which raises the likelihood that small hydrothermal explosions will occur on this edifice in the near future.

## **Landslides**

Although landslides rarely claim lives, they can cause structural damage and can fail rapidly, transitioning into fast moving landslides. Lacroix et al., (*Nature Reviews Earth & Environment*, 2020) studied the life cycle of slow-moving landslides that can creep anywhere from millimeters to several meters per year and can persist for years to decades. They examine the environmental conditions that produce slow-moving landslides, the types of forcings that drive their motion, and discuss what circumstances could result in a rapid failure. With a better understanding of these aspects better forecasts of the onset and triggering of fast moving landslides can be made.

## **Strategic Development and Community Engagement**

The ESI Focus Area continues to work with agency partners, the solid-Earth research community, and other stakeholders to characterize the behavior of the earth system, identify and advance key science objectives, and promote awareness of the program.

ESI's first annual Solid-Earth Team (SET) Meeting occurred November 4-6, 2019, at the Scripps Institution of Oceanography in La Jolla, California. Meeting outcomes were achieved through successful collaboration that transcended ESI. The SET Meeting:

- Created a sense of community by bringing together 130 participants (~ 25% early career, equal NASA and University representation) to engage in 64 posters, 18 lightning talks, 10 program updates, 10 breakout sessions, 6 keynote talks and 3 group discussions.
- Exchanged knowledge and increased communications with particular emphasis on three themes; 1) measurements and technologies to advance solid-Earth science, 2) airborne campaigns and mission development for ESI and 3) raising ESI's profile in the community and beyond
- Identified roughly a dozen science questions, technologies, and group engagement opportunities and strategies for advancing future ESI research and needs

### **Section 1.1.9.5 Water and energy Cycle Focus Area**

NASA's Water and Energy Cycle (WEC) focus area supports research aimed at characterizing the dynamics of and the interactions between the two cycles improving the capability to assess and manage water resources and respond to extreme events. Building on the body of work under 1.1.8 "characterizing the behavior of the Earth system," WEC studies seek to improve understanding of the interacting processes that "control the behavior of the Earth system" and hence "improve predictive capability" as described under performance goal 1.1.9. Improving predictive capability in WEC centers on work towards both physics-based and probabilistic forecasting and includes, to an increasing extent, emerging capabilities in machine learning. With this in mind, studies that inform, or develop capabilities to help improve understanding of the future distribution of water and energy, their inter-relationships and impacts on other Earth systems, and the frequency and intensity of extreme events are classified under 1.1.9. An important goal of the Water and Energy cycle is to develop coupled interactive Earth system models that link the atmosphere, oceans, land masses and biosphere into a comprehensive whole. Section 1.1.9 highlights WEC research that focuses on the broader role of water in the global climate, followed by sections on the variations in local weather/precipitation, hydrological hazards/extreme events, and the role of water in food security.

#### **Water and Climate**

Climate variability and change has occurred throughout history and from an overall WEC perspective, the key questions are to what extent expected climate changes are related to changes in the rate of the Earth's water and energy and cycles, and what trend may be predicted in the future. The water and energy cycle is driven by a multiplicity of complex processes and interactions, many of which are inadequately understood and poorly represented in climate models. The next generation prediction system will be based on a global observing and assimilation system to determine the initial state of climate (especially external and internal forcings) and a modeling system to make forecasts. Developing the prediction capability requires progressing through an iterative cycle of research elements: observations, analysis, model development and testing, evaluation, and demonstration of applications. The following three publications work towards multisensory land data assimilation capability, understanding the influences of sea surface temperatures that influence precipitation, and gaining an understanding about droughts in the southwestern United States as a function of climate change.

Kumar *et al.*, 2019 ([\*Journal of Hydrometeorology\*](#)) described the development and performance of the National Climate Assessment (NCA) Land Data Assimilation System (NCA-LDAS). This system is one of the first successful examples of multisensor, multivariate land data assimilation, encompassing a large suite of soil moisture, snow depth, snow cover, and irrigation intensity environmental data records (EDRs) derived from data from a broad range of satellite-based sensors. Results indicate that multivariate assimilation provides systematic improvements in simulated soil moisture and snow depth, with marginal effects on the accuracy of simulated streamflow and evapotranspiration. Further, drought indicators based on NCA-LDAS output suggest a

trend of longer and more severe droughts over parts of the western United States during 1979–2015, particularly in the southwestern United States, consistent with the trends from the U.S. Drought Monitor, albeit for a shorter 2000–2015 time period.

Gibson *et al.*, 2019 ([Nature Communications](#)) provide a critical review of a previous study describing a teleconnection linking late winter sea surface temperature anomalies in the New Zealand (NZI) region to Southwestern US winter precipitation. An important aspect of their newly proposed teleconnection depends on SSTs in the NZI region leading, and being a source of predictability for, western tropical Pacific SSTs in a region east of the Philippines (EPH). They found little observational evidence that NZI SST anomalies offer a unique source of predictability for EPH SST anomalies and therefore concluded that there is no indication that the proposed NZI index will be a useful source of predictability in future years for Southwestern US winter precipitation.

Williams, *et al.*, 2020 ([Science](#)) use hydrological modeling and a 1200-year tree-ring reconstruction of summer soil moisture to demonstrate that the 2000–2018 southwestern North America (SWNA) megadrought was the second driest 19-year period since 800 CE, exceeded only by a late-1500s drought. The authors found that the trend of 2000–2018 SWNA soil moisture was driven by natural variability superimposed on drying due to anthropogenic warming. The authors estimated that forty-seven percent of the SWNA was caused by anthropogenic climate change.

### **Surface Water**

As we saw in Section 1.1.8, WEC is investing in improving our ability to resolve surface water and measure river discharge, especially as we prepare for the upcoming SWOT Mission. Both are important topics to pursue and to stay current with the advances in land modeling efforts that have moved from a traditional climate paradigm, which disregards horizontal movement of water, to one that models surface processes more comprehensively and at higher spatial resolutions. As our models become more sophisticated, they will begin forecasting key surface water parameters such as dynamic runoff routing, snowmelt and river discharge, and lake levels. The follow pair of publications concentrate on estimating surface water discharge from snowmelt.

First, Li *et al.*, 2020 ([Water Resources Research](#)) quantify the historical and estimated future runoff contribution to extreme floods from Rain On Snow (ROS) within the conterminous United States. Historically, the role of ROS in streamflow extremes is most significant in mid-elevation areas and has been responsible for some of the larger floods in the Western US, however, this “significant influence zone” will shift to higher elevations in a warmer future. The authors conclude that expected changes in the frequency of ROS events will have a first order effect on changes of the runoff contributions from ROS to extreme floods.

The water content of spring snowpack is the most skillful predictor of annual runoff across mountainous regions such as the western United States, as well as prairie regions across the globe. The most certain consequence of anthropogenic climate change will be

a warmer climate, with higher temperatures leading to less snowfall and more rain. Accordingly, Livneh and Badger, 2020 ([Nature Climate Change](#)) show that by mid-century (2036–2065), 69% of historically snowmelt-dominated areas of the western United States will see a decline in the ability of snow to predict seasonal drought, increasing to 83% by late century (2070–2099). When they apply their findings for the US to the globe then it's a strong indication that drought will become less predictable for an estimated two billion people for whom snowmelt currently supplies water.

### **Variations in local weather, precipitation, and water resources**

WEC funds research to characterize variations in local weather patterns, precipitation, and water resources over time to identify and understand the mechanisms driving the hydrologic variability. This is accomplished through the integration of remote sensing imagery with *in situ* datasets, comparative analysis, and numerical models to establish a baseline understanding of varied hydrological systems. Studying these systems over time enables us to understand if the variability is part of a stable cyclic process, influenced by anthropogenic activity, or if the variability is in response to long-term climatic factors. Below are three studies that advanced our knowledge of Atmospheric Rivers (ARs), informally known as in the Western US as “Pineapple Expresses”, which are long, narrow filaments of large vertically-integrated water vapor that concentrates the water content of a typical hurricane with wind speeds to match into a narrow (~100 km wide) ‘firehose.’ Atmospheric Rivers are found globally with significant influence on the west coasts of the United States, Europe and North Africa. Atmospheric Rivers contribute between 30-50% of a region’s annual water budget and are responsible for 90% of the poleward transport of moisture to high latitudes.

DeFlorio *et al.*, 2019 ([Journal of Geophysical Research: Atmospheres](#)) evaluated three operational modeling systems, one each from the U.S., Europe, and Canada, for skill at forecasting Atmospheric Rivers (ARs) out to 4-weeks over the western United States. Ensemble mean biases and skill scores were examined for no, moderate, and high levels of AR activity (0, 1–2, and 3–7 AR days/week, respectively). All hindcast systems were more skillful in predicting no and high AR activity relative to moderate activity. AR hindcast skill along the western U.S. is most strongly increased in hindcasts initialized during Madden-Julian Oscillation (MJO) Phases 1 and 8, and hindcast skill is substantially decreased over California in hindcasts initialized during MJO Phase 4. This research will provide hindcast skill benchmarks and uncertainty quantification for experimental real-time forecasts of AR activity during winters 2019–2021 as part of the subseasonal-to-seasonal Prediction Project Real-time Pilot Initiative in collaboration with the California Department of Water Resources.

Guan and Waliser, 2019 ([Journal of Geophysical Research: Atmospheres](#)) describe enhancements and results (including Atmospheric River (AR) shape, lifetime, travel distance, and mean travel speed) of an algorithm used to track atmospheric rivers from initiation to termination. The results indicate AR genesis is more frequent toward the western boundaries of midlatitude ocean basins and nearby upstream land areas compared to the eastern boundaries and least frequent in tropical and polar areas. AR

termination is more frequent toward the northeastern sectors of the North Pacific/Atlantic and adjacent downstream land areas and in the Southern Ocean near Antarctica compared to the adjacent ocean sectors and least frequent in tropical areas and interior Antarctica where AR genesis is similarly infrequent. Improved AR tracking may have implications to subseasonal and longer-term predictions of AR activity critical to water resources and drought management and identifying flood risks.

Henn *et al.*, 2020 ([Geophysical Research Letters](#)) describe how a 5-day sequence of atmospheric river storms in California, USA, coupled with rapid melt of deep snowpack resulted in extreme inflows to Lake Oroville, damage to the reservoir's spillway infrastructure and evacuation of 188,000 people. The event generated exceptional runoff volumes (second largest in a 30-yr record) partially at odds with the event precipitation totals (ninth largest). The authors explain the discrepancy with observed record melt of deep antecedent snowpack, heavy rainfall extending to unusually high elevations, and high-water vapor transport during the atmospheric river storms. An analysis of distributed snow water equivalent indicates that snowmelt increased. The results highlight potential threats to public safety and infrastructure associated with a warmer and more variable climate.

### **Extreme weather and related hazards**

Some of the most visible and disruptive effects of global climate change are extreme weather and resulting disasters such as wildfires and flooding and the resulting cascading hazards such as landslides and debris flows. These events vary by geographic location, with many regions, such as the Southwest United States and parts of Central and South America, Asia, Europe, Africa and Australia, experiencing more heat, drought and insect outbreaks that contribute to an increase in the number of wildfires. Other regions of the world, including coastal areas of the United States and many island nations, are experiencing flooding and saltwater intrusion into drinking water wells as a result of sea level rise and storm surges from intense tropical storms. Additionally, some areas of the world, such as the Midwestern and Southern United States, have been inundated with rain that has resulted in catastrophic flooding. We highlight a pair of publications that focus on predicting landslides from extreme precipitation events and an article that begins to estimate the spatial-temporal lagged correlation between extreme hydrological floods on land and the resultant freshwater plumes in coastal waters.

Extreme precipitation from the South-Asian monsoon season combines with significant topographic relief within the Himalayan region to cause landslides that result in hundreds to thousands of fatalities each year. While there are few consistent and publicly available in-situ estimates of rainfall across this region, satellite products and global climate models provide insight into the extreme precipitation patterns that impact the frequency of landslides. Stanley *et al.*, 2020 ([Satellite Precipitation Measurement](#)) found that extreme precipitation indices using data from a global climate model and from the NASA TRMM Multi-satellite Precipitation Analysis to successfully model the seasonality of landslide activity across the High Mountain Asia region. Kirschbaum *et al.*, 2020 ([Geophysical Research Letters](#)) present the first

quantitative analysis of potential changes in future landslide activity over the High Mountain Asia region. In doing so, they find that the rate of increase in landslide activity at the end of this century is expected to be greatest over areas covered by current glaciers and glacial lakes, potentially exacerbating the impacts of cascading hazards on populations downstream. This work demonstrates the potential of Global Climate Models and satellite-based precipitation estimates to characterize landslide hazards at time scales affected by climate change.

Fournier *et al.*, 2019 ([Journal of Geophysical Research: Oceans](#)) provide a study of the coupling between specific land regions and coastal river plume structures in the Gulf of Mexico (GoM). The authors found the land basins that were the source regions for plumes in portions of the Gulf of Mexico had varying lead times: northeastern Gulf of Mexico–southeastern Mississippi basin has a 16-day lead time; the northeastern Gulf of Mexico–Mobile Bay basin has a 3-day lead time; and the Central Gulf of Mexico–Texas basin region had a 4-day lead time. In the ocean, they found statistically significant regions of a distinct contribution to plume structure for each of the three sources of freshwater on at lag times from weeks to several months. Though the statistical approach used is limited in its interpretability, the results advance progress toward a predictive framework for mapping the impacts of hydrological flood events from land into the ocean using observations alone.

### **Water Availability**

Characterizing where the water currently resides is a major focus for WEC, as described in 1.1.8 above: forecasting and predicting where water will or will not be utilizes this knowledge to better understand water cycle dynamics and to provide relevant and actionable information for decision makers with added societal benefits. Knowing the water availability for food production and ecosystem viability/stress has wide-ranging benefits especially when economic impacts associated too much or too little can be devastating for many countries. As such, it is critical for water resource managers and the agricultural industry to monitor current and future water supplies and to be cognitive of potential extreme flood and drought events. Science efforts that begin within the Research and Analysis Program (RnA) can evolve to support both RnA research and the broader Applied Science Program end user community. The highlighted publication below is one such study where it utilizes a hydrology forecast model to benefit agriculture and food security.

Arsenault *et al.*, 2020 ([Bull. American Meteorological Society](#)) present a new NASA multimodel, remote sensing–based hydrological forecasting and analysis system, NASA Hydrological Forecast and Analysis System (NHyFAS), developed to support early warning of drought events in Africa and the Middle East. NHyFAS derives increased forecast skill from two sources: (i) accurate initial conditions, produced through the application and/or assimilation of various satellite data, and (ii) meteorological forcing data during the forecast period as produced by a state-of-the-art ocean–land–atmosphere forecast system. An evaluation of NHyFAS shows that its 1–5-month hindcasts successfully capture known historic drought events, and it has improved skill over

## Management and Performance: FY 2020 Annual Performance Report

benchmark hindcasts. Development of the system has benefited from strong collaboration with end-user partners in Africa and the Middle East, who provide insights on strategies to formulate and communicate early warning indicators to water and food security communities. The additional lead time provided by this system will increase the speed, accuracy, and efficacy of humanitarian disaster relief, helping to save lives and livelihoods.

### **Section 1.1.9.6 Weather and Atmospheric Dynamics Focus Area**

For demonstrating progress in **enhancing understanding of the interacting processes that control the behavior of the Earth system, and in utilizing the enhanced knowledge to improve predictive capability**, the WAD invests in understanding precipitation processes, atmospheric dynamics, extreme events including lightning, convective processes, heuristic atmospheric analysis, numerical weather prediction, modeling and data assimilation system improvements. The following sections describe the progress made in the past year (2019-2020).

#### **Better Understanding the Behavior of the Atmospheric Processes**

Understanding the atmospheric water cycle: Worden *et al.* (2019) demonstrated the value of AIRS radiances in retrieving deuterated water vapor, and noted the importance of the long AIRS record for the study of the atmospheric water cycle.

Tracing the source of stratospheric aerosol: Hu *et al.* (2019) used AIRS carbon monoxide, and several other satellite and in situ data sources, to show that Canadian fires were the source of increased stratospheric aerosols over France.

Understanding the propagation of atmospheric gravity waves: Xu *et al.* (2019) used AIRS observations to characterize stratospheric gravity waves over a hurricane, and AIRS cloud top temperature to diagnose storm strength. They also showed that the storm-produced wave train was detected in the mesosphere by the VIIRS imager on Suomi-NPP, and in the ionosphere by GPS satellite receivers.

Reconstruction of the predictor for convective initiation: Kalmus *et al.* (2019) used model wind back-trajectory calculations to reconstruct atmospheric conditions at times and locations of severe convective storms in the U. S. Midwest, showing that these reconstructed atmospheric states are a better predictor of severe storms than conditions observed at overpass. Utilizing AIRS data and this methodology will fill a large time and information gap between Midwestern radiosondes

Double checking the arctic warming trends: Arctic warming was a focus of Susskind *et al.* (2019), who showed that AIRS near-surface temperature trends agree with the NASA Goddard Institute for Space Studies (GISS) trends in global means and over the Arctic during 2003-2018. This study provided independent corroboration of the NASA GISS temperature estimates and received significant media attention.

#### **Model Interfacing in the Joint Effort for Data Assimilation Integration (JEDI)**

Joint weather forecasting data assimilation system development: The Joint Effort for Data Assimilation Integration (JEDI) is a project at the NASA-NOAA-DOD Joint Center for Satellite Data Assimilation (JASDA) for building a data assimilation system for the modern era. It harnesses state of the art object-oriented design practices to build scientific software that is efficient, flexible and easy to use. Central to the idea behind JEDI is that the algorithms used for data assimilation are largely generic and can be built to be useable across centers and thus spread the burden of maintaining that software widely. NASA has embraced the JEDI project as a way to advance the science of data

assimilation for its GEOS model and build a system capable of scaling to NASA's ambitious future plans, such as strongly coupled data assimilation. One of the ways in which JEDI will scale well is by harnessing features of the underlying forecast model. Much effort goes into making GEOS and its dynamical core, FV3, scale well and JEDI is being designed to take advantage of that. The FV3-JEDI interface (Holdaway et al., 2020) is being assembled at GMAO to connect the generic components of JEDI to the GEOS model. It ingests cubed-sphere fields directly from the GEOS model, performs the analysis directly on the cube, and returns analysis fields that can in turn be directly ingested by GEOS. It is already possible to run data assimilation cycles with several algorithms, including those used in current GEOS operations. FV3-JEDI has been connected to the GEOS tangent linear and adjoint model, enabling both a prototype 4D-Var assimilation with GEOS and the porting of the forecast sensitivity-based observation impact (FSOI) diagnostic tools seamlessly to a JEDI-based system. Since FV3-JEDI has been built to be variable-agnostic, it can be used for other atmospheric applications. For example, it has been used to assimilate MODIS observations of aerosol optical depth (AOD). In the future it will be possible to expand FV3-JEDI to also include constituent data assimilation.

### **Improved Prediction of Storm Track and Intensity**

Improving the storm track and intensity prediction: CYGNSS measurements and knowledge gained through the characterization and understanding are also used to improve our ability to predict the Earth system development. Over ocean, the measurements of hurricane winds and the improved storm center location fixes are providing improved predictions of storm track and intensity (Cui et al., 2019).

### **Advancing the Prediction of Precipitation**

Assimilating precipitation into forecasting models: Satellite radiance observations such as from GPM's microwave imager (GMI) combine near global coverage with high temporal and spatial resolution and bring vital information about both clear and cloudy regions to Numerical Weather Prediction (NWP) analyses especially in areas where conventional data are sparse. However, most satellite observations that are assimilated into modeling systems have been limited to clear-sky conditions due to difficulties associated with increased complexity and higher errors in cloudy scenes, and the development of appropriate means of relating model fields to observed cloud- and precipitation-affected satellite radiance data.

Developing the all-sky data assimilation techniques: Kim et al. (2020) provided an overview of the development of a configuration of the Gridpoint Statistical Interpolation (GSI) system to assimilate all-sky data from microwave imagers such as the GMI in the NASA Goddard Earth Observing System (GEOS) model. Data from sensors like GMI are highly sensitive to precipitation. Therefore, all-sky data assimilation efforts are primarily focused on utilizing these data in precipitating regions. To use the microwave data in cloudy and precipitating regions, Kim et al. needed to modify parameterizations for clouds and precipitation in the model and improve the ability to simulate the impact of

cloud microphysics on GMI measurement frequencies, among other improvements. The results from experiments demonstrate the capability of assimilating all-sky microwave brightness temperature data in the GEOS model both when the model forecast produces too much and too little precipitation. Additional experiments show that cloud microphysical and dynamic variables such as winds and pressure are adjusted in physically consistent ways in response to the assimilation.

Understanding the source of weather forecasting predictive skills: Schreck et al. (2020) applied special filtering techniques to a combination of rainfall estimates from TRMM and forecasts from the Climate Forecast System (CFSv2) model. The combined data were filtered for low-frequency variability (time scale of ~120 days), the Madden-Julian Oscillation (30-60 days), and convectively coupled equatorial waves. The filtering on rainfall data provides insight into the sources of skill for the climate model. The low-frequency variability, which encapsulates persistent anomalies generally corresponding with sea-surface temperatures, has the largest contribution to forecast skill beyond 2 weeks. Variability within the equatorial Pacific is dominated by its response to El Niño Southern Oscillation (ENSO), such that both the unfiltered and the low-frequency filtered forecasts are skillful over the Pacific through the entire 45-day forecast. In fact, the low frequency-filtered forecasts in that region are more skillful than the unfiltered forecasts or any combination of the filters. The MJO primarily contributes to model skill over the Indian Ocean, particularly during March–May and certain phases of the MJO. However, the model does not take advantage of MJO-filtered rainfall to contribute to skill in other regions.

Forecasting orographically induced precipitation: Conrick and Mass (2019) evaluate moist physics in the Weather Research and Forecasting (WRF) Model using observations collected during the GPM Olympic Mountains Experiment (OLYMPEX) field campaign and from GMI and DPR. Even though WRF was able to realistically simulate water vapor concentrations approaching the Olympic Mountains, there was underprediction of cloud water content and rain rates offshore and over western slopes of terrain. Conrick and Mass established a connection between cloud water and rain-rate deficits. Comparisons to the GPM data sets showed that WRF produced too little cloud water and rainwater content and excessive snow at higher altitudes. Evaluations of different sectors in the cyclones suggested that postfrontal storm sectors were simulated most realistically, while warm sectors had the largest errors. DPR observations were consistent with GMI in showing the underprediction of rain rates, with no dependence on whether rain occurred over land or water. Finally, WRF underpredicted radar reflectivity below 2 km and overpredicted it above 2 km, consistent with vertical mixing ratio profiles from GMI.

Development of microphysics in forecast models: Satellite retrieval algorithms and numerical weather prediction (NWP) model microphysical parameterizations require information from observations to improve the representation of ice-phase microphysical quantities and processes. Borque et al. (2019) developed a parameterization for ice-phase particle size distributions (PSDs) using in situ measurements of cloud microphysical properties collected during the GPM Cold-Season Precipitation Experiment (GCPEX). The parameterization takes advantage of the relation between a parameter describing the

shape of the size distribution profile and the mass-weighted mean diameter  $D_m$  sampled during GCPEX. The retrieval of effective reflectivity and ice water content (IWC) from the microphysical measurements was tested with independent measurements of these variables and enabled an assessment of the error. The current GPR radar precipitation retrieval algorithm makes assumptions about the particle size distribution, and use of the updated parameterization in this study reduces the bias. Proper selection of the parameterization coefficients in the mass–dimension relationship is also of crucial importance for retrievals.

GMI Clear-sky radiance used for improving storm track and intensity forecast: The impact of assimilating GPM GMI clear-sky radiances on the track and intensity forecasts of two Atlantic hurricanes during the 2015 and 2016 hurricane seasons was assessed by Pu et al. (2019) using the Hurricane Weather Research and Forecasting (HWRF) Model. The GMI clear-sky brightness temperatures were assimilated using the Gridpoint Statistical Interpolation (GSI) data assimilation system, which utilizes the Community Radiative Transfer Model (CRTM) to simulate what satellite sensors observe. Forecast results showed that assimilating GMI clear-sky radiance information produced positive impacts for both storm track and intensity forecasts, with the magnitude of the improvement depending on the phase of hurricane evolution. By comparing forecasts against dropsonde soundings and reanalysis data, they showed that assimilating GMI clear-sky radiances could improve forecasts of thermodynamic variables such as temperature and humidity and dynamic variables such as wind fields and pressure-level heights when the GPM overpass did not overlap with overpasses of other microwave sounders. These forecast improvements in turn led to better track forecasts and a more realistic hurricane inner-core structure. Even when other microwave sounders were present, the assimilation of GMI data still reduced temperature forecast errors in the storm environment, which had a significant impact on the intensity forecast.

### **Improving the Atmospheric Models and Prediction**

Improving convective cloud parameterization: Using AIRS and Suomi NPP orbital-level standard Level-2 (L2), and experimental single field of view (SFOV) retrievals of temperature and water vapor mapped to global deep convective systems, we have learned (Schiro et al. in review) that local (10-50 km) buoyancy and moisture perturbations drive the duration and size of deep convective systems. Such local thermodynamic perturbations were not captured in MERRA-2 analyses, and the results clearly demonstrate the utility of AIRS/SNPP L2 and SFOV retrievals in Earth cloud system process-based analyses. The duration and sizes of deep convective systems influence rainfall extremes and radiative fluxes, and thus, improving model simulations of such systems is crucial. To this end, results are currently informing post-CMIP6 physics development in the NASA-GISS General Circulation Model (GCM), which in turn will facilitate continued improvement of the predictive capability of the GCM.

Use of AIRS And CrIS cloudy radiance in tropical cyclone forecasting: NASA/GMAO has integrated the AIRS Science Team cloud-clearing algorithm that uses spatial information to remove the effects of clouds thereby allowing partially cloudy satellite

data to enter the model. Improvement in operational data assimilation systems: The GMAO team also removed the external dependencies which have hindered the use of cloud-cleared radiances (CCRs) by operational centers. The cloud-clearing algorithm has been parallelized on NASA High-End Computers, with a dramatic improvement in latency, and can produce quasi-real time AIRS radiances that are then assimilated in the GEOS. An extensive set of experiments with the new Hybrid 4D-EnVar system was completed and analyzed. Each experiment comprises more than two months of assimilation, and daily 10-day forecasts issued from each set of analyses, covering most of the 2017 boreal hurricane season (Aug-Oct). Results show that these internally processed CCRs produce a significantly better impact on both global forecast skill and tropical cyclone representation than the assimilation of radiances obtained from the DISC (McGrath-Spangler et al. 2019). The team is currently working to adapt the cloud-clearing algorithm to the production of CrIS radiances optimized for the GEOS system and is performing new experiments. Results were presented at the virtual NSST meeting in May and three peer-reviewed papers are in preparation (one focused on the impact of CCRs in the Arctic region (McGrath-Spangler et al. 2020), one on the impact on Polar Lows (Ganeshan et al. 2020), and the third documenting the revised cloud-clearing algorithm (Boukachaba et al. 2020).

Assimilation of Adaptively Thinned AIRS Cloud-Cleared Radiances in the GEOS: For almost two decades, assimilation of hyperspectral infrared radiances from NASA's Atmospheric Infrared Sounder (AIRS) has provided significant benefit to numerical weather forecasts. However, this improvement stems from the use of highly thinned, cloud-free radiances only, leaving valuable data in cloudy conditions underutilized. While progress has been made assimilating cloud-affected microwave radiances, no forecast center currently assimilates hyperspectral infrared radiances in cloudy conditions. An additional issue with infrared radiance assimilation, as it is currently performed, is the method of thinning. McGrath-Spangler et al. (2019) shows that assimilating cloud-cleared infrared radiances from AIRS with a dynamically adaptive thinning technique improves the representation of various meteorological phenomena, from tropical cyclones to midlatitude baroclinic waves, without degrading the global forecast skill. For tropical cyclones (TC), the adaptive thinning methodology consists of assimilating higher density AIRS cloud-cleared radiances within a moving domain surrounding a cyclone as identified by Best Track information, or alternatively by so-called TC Vitals information in near real-time situations, while assimilating lower density AIRS data elsewhere. By implementing this adaptive thinning methodology in the GEOS data assimilation system it is shown that tropical cyclones were better represented in the analysis and forecast, while simultaneously producing a slight improvement in the hemispheric mid-tropospheric skill scores, as compared with the version of GEOS run in routine operations by the Global Modeling and Assimilation Office (GMAO) at that time.

Improving assimilation of infrared radiances impacted by dust: Using experiment data from the 2013 NASA Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC4RS) we demonstrated that dust contamination can significantly impact modern radiance assimilation of infrared sounders (Oyola et al. 2019). Improvements in aerosol attribution, vertical distribution, and the

choice of optical and surface polarimetric properties were shown to mitigate the majority of dust-induced biases (Marquis et al. 2020).

Improving the Treatment of Microwave Emission Depth for Skin SST Assimilation:

Ebrahimi et al. (2019) investigates the feasibility of assimilating low frequency microwave observations from different satellite microwave radiometers, such as the Global Precipitation Measurement (GPM) Microwave Imager (GMI), the Advanced Microwave Scanning Radiometer 2 (AMSR2) and the Advanced Microwave Sounding Unit-A (AMSU-A). These observations are relevant to the description of air temperature, humidity, and surface parameters such as ocean surface temperature. Their assimilation into the Goddard Earth Observing System (GEOS) modeling and assimilation system helps better constrain the model in regions where very few observations are assimilated. In recent years, surface sensitive channels have not been assimilated in GEOS because of their large sensitivities to uncertain surface parameters, such as emissivity and skin temperature. Skin sea surface temperature (SST) is essential for an atmospheric data assimilation system because it is used to specify the lower boundary condition over the oceans. The analysis scheme requires accurate estimates of SST for direct assimilation of satellite radiance observations, while the atmospheric general circulation model uses it to calculate important variables such as air temperature and air-sea fluxes. This work builds on previous GEOS advancements in the assimilation of surface-sensitive satellite observations in the infrared spectral range. Of particular importance is determining how changes in the penetration depth for different microwave wavelengths affects the measured brightness temperature. It is shown that the effect is negligible for channels with frequencies higher than 10 GHz. However, for the 10 V GHz channel, the impact can be on the order of 0.1K, and for channels at 6.9 and 7.3 GHz the impact can be as large as 0.7 K in some regions. These findings provide critical input for developing observation operators (or forward models) that can accurately simulate ocean surface-sensitive microwave radiances for assimilation into NASA modeling systems.

Study climate forcing and feedbacks: The PCRTM group at NASA Langley has successfully developed a radiometrically consistent climate fingerprinting method that can derive long-term atmospheric trends from various hyperspectral sounders. The PCRTM group processed 16 years of AIRS data and 6 years of CrIS data using the LaRC-developed single field of view (SFOV) Level 2 retrieval and generated a time series of climate anomalies for atmospheric temperature and water vapor profiles, clouds, and surface skin temperatures. This self-consistent high quality data set was used to study the forcing and feedbacks of the CO<sub>2</sub>-induced climate changes (Wu et al. 2020).

Reducing ITCZ biases in climate models: A sampling-bias-corrected AIRS dataset, called Obs4MIPs V2.1 was created for use in future climate Coupled Model Intercomparison Project (CMIP) analyses. Tian and Dong (2020) diagnosed the annual mean double-Intertropical Convergence Zone (ITCZ) bias and the associated annual mean precipitation bias in the latest climate models for CMIP Phase 6 (CMIP6) and compared those to their previous generations (CMIP3 and CMIP5) that were based on the GPCP and TRMM Obs4MIPs precipitation data. They found that all three generations of CMIP models share similar systematic annual multi-model ensemble mean precipitation errors in

tropical oceans. The notorious double-ITCZ bias and its big inter-model spread persist in CMIP3, CMIP5, and CMIP6 models; however, it is slightly reduced in CMIP6.

### **Lightning Prediction and Interactions**

Algorithm development for lightning prediction: SPoRT has developed novel methods to evaluate lightning characteristics of electrified snowfall events from the Geostationary Lightning Mapper (GLM) and the NESDIS merged Snowfall Rate (mSFR) product. It was found that thundersnow flashes observed by GLM have mean flash rates, durations, and total optical energies between the 50<sup>th</sup> and 99<sup>th</sup> percentile values for all flashes within the GLM field of view (Harkema et al. 2019a). Additionally, Harkema et al. (2020) further quantified electrified snowfall events from a GLM perspective. When at least 2 in. of snowfall accumulation occurred, areas with TSSN flashes identified by the thundersnow detection algorithm (TDA) were likely to receive, on average, a total of 24.5 cm (9.6 in.) of snowfall. TSSN was more likely to occur in snowfall rates less than 2.54 cm h<sup>-1</sup> (1 in. h<sup>-1</sup>) and be associated with snow-to-liquid ratio (SLR) values between 8:1 and 10:1.

Development of lightning training products: SPoRT continues to lead the way in improvement of lightning safety research within the stakeholder community. This includes the generation of new products to understand and predict when the last lightning flash occurred over a specific location (e.g., Stano et al. 2019), as well as, using machine learning to predict lightning initiation and propagation 5-15 minutes in advance of occurrence to improve safety at MSFC and in the future other NASA centers. Work with lightning-initiated wildfire also continues. Research has focused on evaluating lightning location relative to precipitation rate and totals near 95 wildfires across the Western US. Findings indicate that the land surface characteristics have more control on fire ignition than the lightning itself (McNamara et al. 2019).

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## **Section 2 Carbon Cycle and Ecosystems Focus Area**

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### **Section 3 Climate Variability and Change Focus Area**

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## **Section 5 Water and energy Cycle Focus Area**

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